Holographic Black-Hole Cosmology and the Informational Dynamics of Spacetime: An Informational Solution to the Hubble Tension and the Arrow of Time

Heath W. Mahaffey[1, *]

[1] *Independent Researcher*

(Dated: December 6, 2025)

We present a cosmological framework in which the expansion of spacetime is interpreted as a geometric necessity driven by the informational requirements of the holographic horizon. Integrating the Bekenstein-Hawking entropy bounds with a quantum theory of distinction actualization, we posit that the universe acts as an information processing system where the collapse of quantum potential into physical distinctions generates an informational pressure on the boundary. We derive a modified Friedmann equation where the Hubble parameter $H(t)$ is a function of the global information production rate $\dot{I}(t)$. We decompose this rate into two components: a constant vacuum term (recovering Dark Energy) and a time-dependent structural complexity term. This model offers a novel resolution to the **Hubble Tension**: the discrepancy between early-universe (CMB) and late-universe (local) measurements of H_0 arises because the emergence of cosmic structure (galaxies, stars) accelerates the rate of information encoding, thereby necessitating a faster expansion rate in the local epoch than standard ΛCDM predicts.

I. INTRODUCTION

The standard ΛCDM model of cosmology successfully describes the large-scale structure of the universe but faces significant theoretical challenges. Foremost among these are the physical origin of the Cosmological Constant (Λ), the thermodynamic origin of the Arrow of Time, and the "Hubble Tension"—the statistically significant discrepancy between expansion rates measured in the early versus late universe [1, 2].

Concurrently, developments in quantum gravity, specifically the Holographic Principle [3, 4], suggest that the maximum entropy of a region scales with its boundary area rather than its volume. This implies a fundamental link between geometry and information.

In this paper, we propose the **"I AM" (Informational Actualization Model) Hypothesis**, which inverts the standard causal order of cosmology. We posit that the universe does not expand to contain matter; rather, it expands to encode information. Specifically, we argue:

1. **Ontology:** Reality consists of the continuous transition from quantum potential (superposition) to physical actualization (distinct states).
2. **Holography:** Every actualized distinction acts as a "bit" that must be encoded on the cosmic horizon.
3. **Dynamics:** To prevent the violation of entropy bounds, the horizon area must grow to accommodate new information. This growth is perceived as cosmic expansion.

This framework provides a physics-only mechanism for the Arrow of Time and resolves the Hubble Tension by linking expansion velocity to the complexity of cosmic structure.

* hmahaffeyges@gmail.com

II. THE INFORMATIONAL METRIC

A. The Holographic Constraint

We begin with the Bekenstein-Hawking entropy for a horizon of area A_H. In Planck units ($c = \hbar = G = k_B = 1$):

$$S_{BH} = \frac{A_H}{4} \tag{1}$$

This implies a strict limit on the information capacity (I_{max}) of the universe. Identifying the horizon with the Hubble radius $R_H = 1/H$, the area is $A_H = 4\pi/H^2$. Thus, the instantaneous information capacity is:

$$I(t) \propto \frac{1}{H(t)^2} \tag{2}$$

Standard cosmology treats $H(t)$ as the independent variable driving the observable horizon. We propose that $I(t)$—the information content of the bulk—is the driving variable. If the bulk information content grows, $H(t)$ must decrease (and the radius $1/H$ must increase) to satisfy the holographic bound.

B. The Modified Friedmann Ansatz

We propose that the square of the Hubble parameter is proportional to the time derivative of the information content, $\dot{I}(t)$. The expansion of space is the geometric response to the "bit-rate" of reality.

$$H(t)^2 = \beta \frac{dI}{dt} \tag{3}$$

where β is a coupling constant with dimensions $[L^2T^{-1}\text{bit}^{-1}]$.

III. DISTINCTION ACTUALIZATION AND THE VACUUM

A common critique of entropic gravity models is the "Empty Universe" problem: Why does a de Sitter universe with no matter expand? We address this by defining the components of $\dot{I}$.

We decompose the total information production into a vacuum term and a structural term:

$$\frac{dI}{dt} = \dot{I}_{vac} + \dot{I}_{struct}(t) \tag{4}$$

A. The Vacuum Term (Dark Energy)

The quantum vacuum is not empty; it is a reservoir of infinite potential characterized by continuous virtual particle fluctuations. We posit that the transient actualization of virtual pairs constitutes a baseline rate of distinction formation.

$$\dot{I}_{vac} = \Lambda_{info} \quad \text{(constant)} \tag{5}$$

Even in the absence of matter, the vacuum "processes" potential into entangled states. This constant informational pressure forces the horizon to expand, recovering the Cosmological Constant (Λ) of General Relativity naturally.

B. The Complexity Term

The second term, $\dot{I}_{struct}(t)$, represents the information generated by irreversible processes in matter: gravitational collapse, stellar fusion, and chemical evolution. We introduce a **Complexity Function** $C(z)$, dependent on redshift z:

$$\dot{I}_{struct}(z) \propto C(z) \tag{6}$$

In the early universe (Radiation domination), particle interactions were high-energy but structurally simple (maximum entropy, minimum complexity). In the late universe, gravity has formed highly complex, information-dense structures (galaxies, generic observers).

IV. RESOLUTION OF THE HUBBLE TENSION

The Hubble Tension arises because H_0 inferred from the Cosmic Microwave Background (CMB) ($z \approx 1100$) is significantly lower than H_0 measured from local Supernovae ($z < 2$).

Using Eq. (3), we can analyze the expansion rate at different epochs.

A. Epoch 1: Early Universe (CMB)

At high redshift, structure formation is negligible ($C(z) \to 0$). The expansion is driven primarily by the vacuum baseline and simple fluid dynamics.

$$H^2_{early} \approx \beta \dot{I}_{vac} \tag{7}$$

This corresponds to the lower value of H_0 ($\approx$ 67.4 km/s/Mpc).

B. Epoch 2: Late Universe (Structure Era)

In the modern epoch, the universe is filled with distinct structures. The rate of distinction actualization has increased due to the complexity of the "computational" state of the universe.

$$H^2_{local} \approx \beta(\dot{I}_{vac} + C_{max}) \tag{8}$$

The additional term βC_{max} represents the extra expansion velocity required to encode the increased informational load of a complex universe.

C. Prediction

Our model predicts that $H(z)$ does not follow a pure ΛCDM curve. Instead, it predicts a **Complexity-Induced Acceleration**: the expansion rate should deviate from the standard model exactly during the epoch of peak star formation and galaxy assembly ($z \sim 1 - 2$). This explains why local measurements yield a higher H_0 than early universe predictions.

V. THE ARROW OF TIME

Standard thermodynamics attributes the arrow of time to entropy increase. However, this raises the question of why the initial state was low entropy. In the "I AM" framework, time is defined as the accumulation of distinctions:

$$t_{arrow} \equiv \int \frac{dA_H}{4\dot{I}} \tag{9}$$

Time flows in the direction of distinction actualization.

- **Future:** The realm of un-collapsed quantum potential (Superposition).
- **Past:** The realm of holographically encoded distinctions (Fixed information).
- **Now:** The boundary of actualization.

Time cannot reverse because doing so would require "uncollapsing" a distinction. By Landauer's Principle, erasing information requires energy dissipation, which increases the total entropy of the surroundings. Thus, the Informational Arrow of Time is strictly monotonic.

VI. DISCUSSION

A. Physics-Only Framework

While the terminology of "distinction" and "observation" overlaps with Wheeler's "It from Bit" [5], this model avoids idealism or panpsychism. A "distinction" is a physical decoherence event, independent of conscious observation. The "observer" in this model is the holographic boundary itself, which must account for all degrees of freedom.

B. Implications for Quantum Gravity

This hypothesis suggests that the metric of spacetime ($g_{\mu\nu}$) is not a fundamental field, but an emergent property of the entanglement structure required to store information. This aligns with recent work in ER=EPR and tensor network cosmologies [6], but adds a specific mechanism (complexity growth) for the acceleration of expansion.

VII. CONCLUSION

We have presented a holographic cosmological model where expansion is the physical manifestation of information storage. By modifying the Friedmann equation to include a term for structural complexity, we provide a unified explanation for:

1. **Dark Energy:** The baseline information pressure of the quantum vacuum.
2. **The Hubble Tension:** The acceleration of expansion due to the increasing complexity of the late universe.
3. **The Arrow of Time:** The irreversible accumulation of encoded distinctions.

This suggests that the universe is a self-updating informational structure, where geometry emerges from the dynamics of quantum potential.

[1] A. G. Riess et al., "Large Magellanic Cloud Cepheid Standards Provide a 1% Foundation for the Determination of the Hubble Constant and Stronger Evidence for Physics beyond ΛCDM," *Astrophys. J.* **876**, 85 (2019).

[2] Planck Collaboration, "Planck 2018 results. VI. Cosmological parameters," *Astron. Astrophys.* **641**, A6 (2020).

[3] G. 't Hooft, "Dimensional Reduction in Quantum Gravity," arXiv:gr-qc/9310026 (1993).

[4] L. Susskind, "The World as a Hologram," *J. Math. Phys.* **36**, 6377 (1995).

[5] J. A. Wheeler, "Information, physics, quantum: The search for links," in *Complexity, Entropy, and the Physics of Information*, Addison-Wesley (1990).

[6] J. Maldacena and L. Susskind, "Cool horizons for entangled black holes," *Fortsch. Phys.* **61**, 781 (2013).