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Astrophysical Constraints on the Simulation Hypothesis for This Universe from a Biological Point of View

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Abstract

We have examined the Simulation Hypothesis through an interdisciplinary lens, combining insights from physics, biology, and psychology. Building on recent evidences on quantitative critique, we propose an alternative computational paradigm inspired by biological information processing. Rather than a continuous "brute-force" simulation, we suggest an event-driven, observer-dependent model that dramatically reduces computational requirements. Using the adaptive immune system as an analogy, we demonstrate how sparse computation can manage vast potential information spaces efficiently through a quantitative framework distinguishing potential from active entropy. This framework aligns with relational interpretations of quantum mechanics and offers a resolution to the physical impossibilities identified in continuous simulation models. Our aim is not to provide a constructive simulation design within known physics, but to show that alternative, biologically inspired paradigms re-open conceptual space that previous analysis, by construction, leaves unexamined. Additionally, we explore the psychosocial dimensions of the Simulation Hypothesis, examining why observer-dependent ontologies resonate in contemporary discourse and how they intersect with broader cultural patterns of meaning-making.

Keywords: simulation hypothesis; event-driven computation; adaptive immune system; relational quantum mechanics; information entropy; observer-dependent reality

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Introduction

The Simulation Hypothesis (SH) has attracted growing attention across physics, philosophy, and popular culture, raising the question of whether our universe might itself be the product of an underlying computational process. A number of recent works have attempted to quantify the physical resource requirements of such a simulation, often concluding that straightforward, continuous, high-resolution simulations of an entire universe would demand unattainable amounts of energy and information processing [1]. These analyses typically assume that a simulator must evolve all relevant degrees of freedom—at Planck-scale or coarser resolutions—at all times.. In this article we explore a different computational paradigm for thinking about simulated universes. Rather than assuming a continuous, exhaustive evolution of all states, we take inspiration from biological information processing—specifically the adaptive immune system—to develop an event-driven, sparse, and observation-dependent model. The central idea is that a simulator might encode an enormous latent state space while only ever computing a tiny subset of states that become relevant through concrete interactions. This model dramatically alters the computational requirements by positing that reality is rendered "on-demand" upon interaction, and may circumvent some of the physical impossibilities attributed to continuous, brute-force simulations. Inspired by the principles of efficiency in biological systems, specifically the immune system, we suggest a more plausible simulation paradigm: one that is **event-driven, sparse, and observation-dependent**.The proposal of an observer-dependent reality has profound philosophical implications, which leads us to examine the psychosocial underpinnings of the SH itself—a dimension that, while often overlooked in physical analyses, is crucial for a complete understanding of the hypothesis's enduring appeal. Our aim is not to provide a constructive simulation design within known physics, but to show that alternative, biologically inspired paradigms re-open conceptual space that continuous, brute-force analyses, by construction, leave unexamined.

A Quantitative Analogy: The Information Entropy of the Immune System

Biological systems master complexity through reactive, decentralized mechanisms that operate on principles fundamentally different from brute-force computation. The adaptive immune system is a prime example. Through V(D)J recombination, the human body generates a potential diversity of T-cell receptors (TCRs) estimated to be as high as 10^{15}. This represents an immense reservoir of **potential information**, a pre-calculated library of solutions to threats that have not yet occurred [2,3]. Let N_{pot} denote the total number of distinct TCR configurations generated in principle by V(D)J recombination, and N_{act} the number of distinct TCR clones that are actively involved in responding to a given infection. The **potential entropy** H_{pot} is the Shannon information required to specify a single receptor chosen from the full repertoire:

$$H_{\text{pot}} = \log_2 N_{\text{pot}}$$

The **active entropy** H_{act} is the information required to specify one clone among those actually engaged in the response:

$$H_{\text{act}} = \log_2 N_{\text{act}}$$

We then define a **Computational Load Reduction Factor** Λ as the ratio of active to potential states:

$$\Lambda = \frac{N_{\text{act}}}{N_{\text{pot}}} = 2^{H_{\text{act}} - H_{\text{pot}}}$$

which quantifies how much smaller the operational load is compared to the full latent information capacity of the system.

For the human immune system, the potential Shannon entropy representing the information required to specify one unique receptor out of all possibilities is approximately:

$$H_{\text{pot}} = \log_2 (10^{15}) \approx 50 \text{ bits}$$

However, the crucial point is that the system does not actively compute or render all 10^{15} states simultaneously. Instead, it operates on a principle of selective activation. During an infection, only a tiny fraction of T-cell clones that recognize a specific antigen—say, 10^6 clones—are activated and proliferate [4,5]. This "computation" is a highly specific, localized cascade involving signaling molecules like **interleukins and interferons**, representing an event-driven response to a query (the antigen).

For illustration, suppose the potential TCR repertoire is on the order of $N_{\text{pot}} \sim 10^{15}$, while a particular infection effectively recruits $N_{\text{act}} \sim 10^6$ distinct clones. In that case:

$$\Lambda \sim \frac{10^6}{10^{15}} = 10^{-9}$$

corresponding to a nine-order-of-magnitude reduction in the number of states that must be actively "tracked" at a given time. The exact values are model-dependent, but the qualitative point is robust: a system may encode an astronomically large latent space yet operate on a minuscule, context-dependent subset.

The active entropy related to the information of the observed state is thus:

$$H_{\text{act}} = \log_2 (10^6) \approx 20 \text{ bits}$$

This illustrates that the system's operational load is not proportional to its vast potential complexity but to its minuscule observed state, reduced by a factor of approximately one-billionth. This biological paradigm—of vast latent information and sparse, event-driven computation—serves as a powerful model for a viable simulation.

Quantum Mechanics in an Event-Driven Simulation

A crucial objection to any sparse simulation model is its compatibility with quantum mechanics. As has been noted, simply using coarse time-steps (Δt) in unobserved regions to speed up computation would lead to violations of the energy-time uncertainty principle [1]:

$$\Delta E \cdot \Delta t \geq \frac{\hbar}{2}$$

This would fundamentally alter physical laws like nuclear decay and electromagnetism, which have been tested with extreme accuracy. However, our proposed model is not one of coarse-graining, but of **computational potentiality**. The simulation does not render a low-resolution reality in unobserved states; rather, it upholds a set of rules and probabilities that exist in a state of latency. This paradigm aligns closely with relational interpretations of quantum mechanics (e.g., Rovelli, 1996), which posit that a system's properties are only defined upon interaction with another system [6]. It is important to clarify what we mean by "observer" in this observer-dependent model. In line with relational interpretations of quantum mechanics, we do not restrict observers to conscious biological agents; rather, any physical system that interacts with another system and thereby establishes relational properties counts as an observer for that interaction. A measurement apparatus in a laboratory, a distant star, or even an elementary particle can, in this sense, play the role of observer when it participates in an interaction that fixes otherwise merely potential properties into an actualized outcome. Conscious observers, such as human beings, then form a special subclass of these physical observers, but are not ontologically privileged in the basic dynamical scheme.In our model, the "computation" of a quantum state—with all its inherent uncertainty and probabilistic nature—occurs precisely at the moment of interaction or measurement. Therefore, any experiment designed to test Quantum Field Theory would be rendered with full quantum fidelity, because the act of measurement *is* the event that triggers the computation. The simulation doesn't suppress or violate quantum mechanics; it treats it as a computable, relational phenomenon, thereby remaining consistent with the vast body of experimental evidence.A natural concern is whether an event-driven simulation must secretly maintain a continuously updated global state in order to reproduce quantum entanglement and nonlocal correlations. In a relational view, however, what must be reproduced are the observable joint probabilities of measurement outcomes, not a globally defined wavefunction at all times. An event-driven simulator need only compute the correlations at the moments when entangled systems are jointly measured, using stored rules and relative states, rather than evolving a fully explicit, global quantum state at every intermediate step. This approach does not invoke hidden variables but instead exploits the fact that quantum mechanics provides deterministic rules for calculating correlation functions and measurement statistics from prepared states—computation can be deferred until observation events actually occur.

Implications for the Simulation Hypothesis

The same distinction between latent and active information can, at least schematically, be applied to cosmological simulations. Vazza's calculations effectively assume that the simulator must track a "potential entropy" corresponding to all degrees of freedom of the cosmic volume at all times; our proposal is that only an "active entropy" associated with actually realized observations needs to be computed, with an analogous reduction factor Λ_{cosm} relating the two. Even if Λ_{cosm} were far less extreme than in the immune system, any systematic reduction by many orders of magnitude would qualitatively change conclusions about feasibility.Applying this event-driven principle, the computational cost of a universal simulation is no longer tied to the total theoretical information (I_{tot} bits) but to the far smaller set of actively observed information (H_{act}). The required energy (E_{sim}) would thus be:

$$E_{\text{sim}} \ll k_B T \ln(2) \cdot I_{\text{tot}}$$

where the symbol $\ll$ indicates "much less than."

Crucially, this principle applies not only to the astronomical information content of the entire cosmos but is even more critical for making lower-resolution simulations, such as planet-scale or galaxy-scale models often considered in the literature, computationally feasible. Analyses that treat such simulations as continuously running still face prohibitive resource requirements, whereas an observer-dependent scheme would only compute those interactions that actually occur within the system. The universe would exist as a compressed set of rules, actualized locally and sparsely only when a question is asked of it through physical interaction. More concretely, by a "compressed set of rules" we mean that the simulator need not store a fully explicit description of all physical states at all times, but only a finite algorithmic procedure capable of generating local states when required. This is analogous to procedural generation in modern video games, where complex terrains or entire planets are not pre-rendered and kept in active memory, but are instead generated on demand when the player's viewpoint reaches a given region. In our context, the latent "world" is encoded as algorithms and parameters, and only those spacetime regions that are actually involved in interactions or observations need to be instantiated into explicit states. By analogy with the immunological case, we can introduce a speculative cosmological Load Reduction Factor Λ_{cosm}, defined as the ratio between the information associated with actually instantiated macroscopic configurations and the total latent information capacity of the cosmic model. In this picture, not only quantum measurements but a wide range of macroscopic processes could act as "triggers" for active computation: the formation of bound structures (such as galaxies and planetary systems), thermodynamic irreversibility in far-from-equilibrium processes, or the operation of complex information-processing systems (including, but not limited to, biological organisms and technological devices). Whenever such processes require the specification of concrete outcomes—e.g., which side of a bifurcation a chaotic system follows, or which specific microscopic configuration realizes a macroscopic macrostate—the simulator need only compute and store those aspects of the state space that are relevant to the ensuing relational network of interactions. Although we cannot presently estimate Λ_{cosm} quantitatively, the conceptual role is clear: even a modest systematic reduction in the fraction of states that must be explicitly realized at macroscopic scales would significantly relax previously theory style bounds on the feasibility of a simulation. Figure summarizes this contrast between continuous computation and event-driven reality, and illustrates how the distinction between potential and active entropy underlies the proposed sparse simulation paradigm

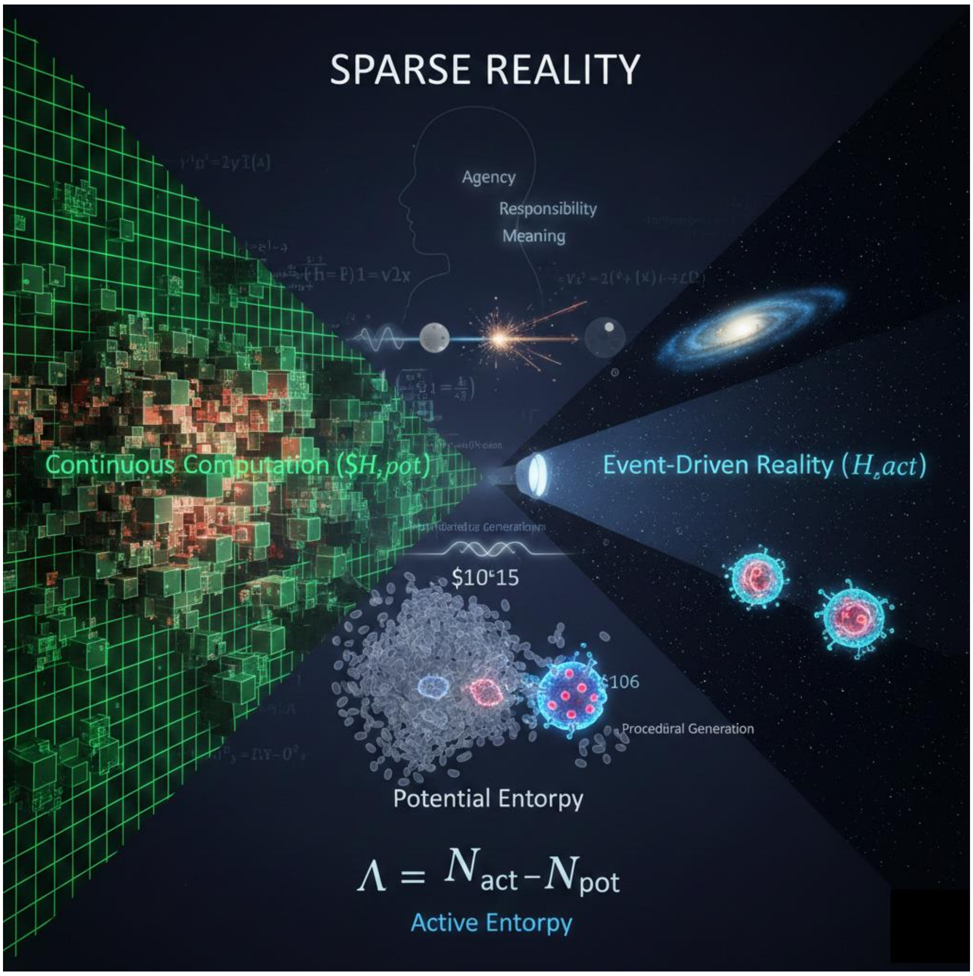

Figure 1. Sparse reality as an event-driven simulation. Schematic contrast between a continuous, brute-force simulation (left) and an event-driven, observer-dependent reality (right). The lower panel illustrates the distinction between potential entropy (full latent repertoire, N_{pot}) and active entropy (realized states, N_{act}), quantified by the Computational Load Reduction Factor Λ, and suggests how these ideas might extend from the adaptive immune system to cosmology and agency.

Psychosocial Dimensions: The Appeal of Existential Externalization

Notably, the same observer-dependence that makes an event-driven simulation computationally attractive also resonates with deep psychological and cultural patterns in how we ascribe meaning to the world. The proposal of an observer-dependent simulation, where reality is rendered upon interaction, inherently elevates the role of the conscious observer. This shift from a "brute-force" universe to an "on-demand" one has profound philosophical and psychological implications. It forces us to ask *why* such a hypothesis is intellectually and emotionally appealing. The theory that we live in a simulation may fulfill a deep psychosocial need to externalize responsibility for our existence. This exploration builds upon a rich philosophical tradition that questions the nature of reality itself, most famously articulated in Bostrom's (2003) foundational tripartite argument for the simulation hypothesis and more recently explored by Chalmers (2022), who argues that virtual worlds are genuine realities [7,8]. By positioning ourselves as inhabitants of a computational construct, we may unconsciously seek refuge from the weight of moral agency and accountability. This represents a form of existential escapism, a reflection of our collective anxiety about meaning in an increasingly complex world.It is therefore unsurprising that a hypothesis which both elevates the observer in the physical description of reality and externalizes ultimate responsibility for that reality should gain traction in a cultural landscape marked by uncertainty and complexity.Of course, not all engagement with the Simulation Hypothesis is escapist. For many, it functions as an epistemic instrument, a way of probing the limits of scientific realism and the underdetermination between "base" and "simulated" worlds; our point is that these intellectual motives coexist with, and are often amplified by, more affective dynamics of externalization.

Discussion

Existing quantitative analyses provide a robust refutation of straightforward “brute-force,” continuous simulations occurring within a universe constrained by our known physics [1]. The framework proposed here suggests that this refutation is directed at a particular computational architecture—continuous, brute-force computation of all states—rather than at the Simulation Hypothesis as such [1]. By invoking an analogy from immunology—a system that manages immense potential information through sparse, event-driven computation—we propose an alternative model. This framework, where reality is rendered upon observation, is not only more computationally efficient but also aligns with relational interpretations of quantum mechanics and the foundational ambitions of AI. A universe governed by computable rules rather than continuous, brute-force computation, is not obviously ruled out as a simulation by the sorts of constraints discussed in the existing literature [1]. This work, therefore, complements existing physical calculations with an interdisciplinary lens that encompasses not only the physics and biology of information but also the human psychology that drives our fascination with our own existence. Whether or not we live in a simulation, we must grapple with the profound responsibility that comes with consciousness and with the very real consequences of our choices in this, at the very least, experientially real universe.

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