Emergent Spacetime from Self-Referential Computation: A Hierarchical Cellular Automaton Framework

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Abstract

This paper proposes a cosmological model — the Singularity-Bounded Holographic Class 4 Automaton (SB-HC4A) — derived from the convergence of four independently motivated frameworks: a five-class computational taxonomy that refines Wolfram's (2002) classification by separating fractal from random dynamics, a theoretical framework for self-referential computation in self-modeling systems (Gruber, 2015, 2026a, 2026b) which identifies self-referential simulation at criticality as a universal computational pattern, and 't Hooft's (1993, 2016) holographic automaton interpretation of quantum mechanics. The model proceeds by elimination: Classes 1–3 cannot sustain the universal computation the universe demonstrably supports; Class 5 (genuine randomness) makes physics fundamentally impossible; therefore the universe operates at Class 4 — the edge of chaos. Combined with the information-theoretic observation that singularities at every physical scale (Planck regime, particle interiors, event horizons, cosmological horizons, temporal endpoints) share the property of information impermeability and Bekenstein saturation, the model proposes that these singularities are structurally identical — scale-invariant instances of the same information boundary. The resulting architecture is a self-referential holographic Class 4 automaton bounded at every scale by singularity surfaces, where the observable interior is the "simulation" and the singularity boundary is the "substrate." All singularities — including temporal endpoints — are shown to be asymptotically unreachable from within the computational domain, strengthening the unification claim. Because singularities transform rather than destroy information, heat death constitutes a singularity transition that triggers cyclic renewal, with potential CPT signature alternation across cycles — connecting to Penrose's Conformal Cyclic Cosmology and Boyle and Turok's CPT-symmetric universe. All three cosmological endgames — heat death, Big Crunch, and Big Rip (Caldwell, 2002) — drive the computational domain to Bekenstein saturation, with the Big Rip uniquely producing a branching tree of daughter universes rather than a linear successor. This architecture is structurally identical to self-referential computational systems that operate at criticality, where implicit knowledge (substrate) is separated from explicit representation (simulation)

by an information-opaque boundary. Self-modeling cognitive systems are thus local, scale-reduced instances of the same computational pattern the universe implements globally. Six weak points are identified, including the fundamental epistemological objection that Class 4 observers may be constitutionally incapable of determining whether this model describes the universe or merely the ceiling of their own computational capacity.

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1. Introduction

1.1 The Problem

A fundamental question in cosmology is: *Why does the universe have the structure it has?* This paper proposes that the universe's architecture — its dynamics, boundaries, and self-organizing properties — follows from a unique computational pattern: self-referential computation at criticality. This pattern appears not only at cosmological scales but also in self-modeling cognitive systems, suggesting a universal principle rather than a cosmic accident.

The argument proceeds from structural constraints. If certain axioms hold — ontological necessity, computational character, criticality stability, information bounds, and holographic encoding — then a unique architecture emerges: a self-referential holographic automaton operating at the edge of chaos, bounded at every scale by information-impermeable singularities. This is not merely one possible universe structure among many, but the unique self-consistent configuration for a system that computes its own existence.

1.2 Sources and Scope

The model presented here draws on four bodies of work:

1. **The Five-Class Computational Taxonomy** (Gruber, 2015), which refines Wolfram's (2002) four-class classification of dynamical systems by splitting his Class 3 ("random") into genuine fractals (the new Class 3) and genuine randomness (the new Class 5). This produces a clean monotonic gradient from order to disorder and reveals that Class 4 — the edge of chaos — is the maximum complexity achievable by expressible rules.

2. **A framework for self-referential computation** (Gruber, 2015, 2026a, 2026b), originally developed in the context of self-modeling systems, which identifies self-referential simulation at criticality as a universal computational pattern. The framework distinguishes implicit knowledge (substrate-level representation) from explicit representation (simulated representational content), with an information-opaque boundary between them, and

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establishes self-referential closure as a fixed point: $\Phi(\mathrm{m}) = m$. This pattern appears in any system that models its own modeling processes.

3. **The Holographic Automaton Interpretation** ('t Hooft, 1993, 2016), which proposes that quantum mechanics emerges from deterministic dynamics at the Planck scale — that the universe is fundamentally a cellular automaton whose holographic structure produces quantum behavior as an emergent phenomenon. Recent work by Wetterich (2022a, 2022b, 2022c) has demonstrated that this is not merely philosophical — specific cellular automata are mathematically equivalent to fermionic quantum field theories, including a model of spinor gravity in four dimensions with exact local Lorentz symmetry.

The model is speculative. It is not a proof. It is a logical argument chain that, if the premises hold, yields a specific cosmological architecture. The paper presents the argument, identifies where it could break, and proposes what would count as evidence for or against it.

1.3 Acknowledgment

The importance of symmetries in physical theory — the methodological principle that drove this work — was impressed upon me by my uncle, Bruno J. Gruber, a theoretical physicist who has spent his career working on symmetry groups in quantum mechanics (Gruber, 1968, 1980). The observation that the same computational architecture might appear at multiple scales is, at bottom, a symmetry claim. Whatever merit it has owes much to his influence.

The self-referential computation framework draws on Thomas Metzinger's self-model theory of subjectivity (Metzinger, 2003) as a source for the computational pattern, though the present work applies it to cosmological rather than cognitive questions. The idea that the universe might be a cellular automaton operating under holographic constraints was already present in embryonic form in my 2015 book, where 't Hooft's holographic bound was discussed in a cosmological context (Gruber, 2015, pp. 79–80). The full SB-HC4A architecture developed here represents the mature formulation of those early intuitions.

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2. The Five-Class Framework

2.1 Wolfram's Classification and Its Problem

Wolfram (2002) classified the behavior of cellular automata into four classes based on their long-term dynamics:

Wolfram Class	Behavior	Example
1	Uniform (converges to fixed state)	Rule 0
2	Periodic (settles into repeating loops)	Rule 4

Wolfram Class	Behavior	Example
3	Random/chaotic (apparently random)	Rule 30
4	Complex (persistent interacting structures)	Rule 110

This classification was genuinely useful and applied far beyond cellular automata — to fluid dynamics, biological systems, economic models, and neural networks. But Wolfram's Class 3 was a grab-bag containing two structurally different phenomena: fractal systems like Rule 90 (which generates a Sierpinski triangle — computationally *reducible*, meaning you can calculate any cell without running the full simulation) and apparently chaotic systems like Rule 30 (which produces output that *looks* random but is completely deterministic and computationally *irreducible*).

Rowland (2006) independently argued that nested (fractal) patterns deserved separate classification. I argue the distinction goes deeper: fractal and genuinely random systems differ in a way that matters for cosmology.

2.2 The Five Classes

The refined classification, ordered as a monotonic gradient from most ordered to most disordered:

Class 1 — Static. Systems that converge to a fixed state. Period: 1. No computation.

Class 2 — Periodic. Systems that settle into repeating loops. Information is stored but never transformed. Period: finite.

Class 3 — Fractal. Systems that produce self-similar structure at every scale. Computationally *reducible* — you can skip ahead without running every step. Structure without processing power. Period: quasi-infinite with exact or statistical self-similarity.

Class 4 — Complex (edge of chaos). Systems that produce persistent localized structures capable of arbitrary computation. Computationally *irreducible* — no shortcuts. These systems support universal computation: given the right initial conditions, they can simulate any algorithm, including themselves. This is where self-referential computation emerges.

Class 5 — Random. Systems whose output is genuinely random — maximal Kolmogorov complexity, incompressible, non-algorithmic. The generating process exceeds what formal symbolic systems can express.

2.3 Why Deterministic Rules Cannot Produce Randomness

A cellular automaton has a finite rule table and a finite initial condition — together, a fixed finite amount of information. A truly random infinite sequence has maximal Kolmogorov complexity and cannot be compressed to anything

shorter than itself. Therefore, no deterministic automaton can produce genuinely random output: the output's complexity is bounded by the rule-set's complexity (Kolmogorov, 1965; Chaitin, 1966).

This is a generalized pigeonhole argument. The only way to generate infinite output from finite information is to reuse structure at different scales. Exact reuse is periodicity (Class 2). Patterned reuse is fractal behavior (Class 3). Even the most complex-looking automata — Rule 30, Rule 110, Conway's Game of Life — produce output whose complexity is bounded by their rule-set.

What Wolfram called "random" automata are better described as *high-complexity fractals*: systems whose self-similar structure operates at scales and in dimensions that make it invisible to casual inspection.

2.4 Class 4 as the Expressibility Ceiling

Classes 1 through 4 are what finite, expressible rules can produce. Class 5 requires rules that cannot be written down — if the rule were expressible, the output would be compressible (to: "apply this rule"), and therefore not truly random.

Class 4 is therefore the *maximum complexity achievable by expressible rules.* It is as complex as mathematics can get. Beyond it lies territory that formal systems, by their own nature, cannot map.

This observation — that expressible computation has a ceiling, and that ceiling is Class 4 — is the first premise of the cosmological argument.

2.5 Class 4 Contains All Classes Including Itself

A critical property: Class 4 automata can generate Class 1 behavior (stable states), Class 2 behavior (oscillations), and Class 3 behavior (fractal patterns) as subprocesses within their own dynamics. No lower class can do this. The Game of Life, for instance, contains still lifes (Class 1), blinkers (Class 2), and self-similar growth patterns (Class 3) as embedded phenomena within its Class 4 dynamics.

This containment property means that a Class 4 universe does not merely permit lower-class phenomena — it *generates* them. Static matter, periodic orbits, fractal coastlines, and self-similar galaxy distributions are all Class 4 subprocesses.

But the most consequential containment is self-containment: Class 4 automata can contain Class 4 automata as subprocesses. This follows directly from universality — a Turing-complete system can simulate any Turing machine, including another Turing-complete system (Cook, 2004, proved this for Rule 110). No lower class possesses this property; Classes 1–3 cannot generate dynamics at or above their own complexity. Class 4 is the only class that can nest instances of itself within its own dynamics. The contained instance is

necessarily resource-constrained — fewer effective cells, slower clock — but it is genuinely Class 4: capable of universal computation, supporting criticality, and itself capable of containing further Class 4 subprocesses. This self-nesting property is the structural foundation for the cross-scale identity developed in Section 7: if the universe is a Class 4 automaton, then any sufficiently complex subsystem operating at criticality within it — including a brain — is itself a Class 4 automaton embedded within the larger one.

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3. The Universe Must Be Class 4

3.1 The Ontological Starting Point

Pure nothingness cannot exist as a state of affairs. "Nothing" is a Platonic abstraction — like a perfect circle or a truly periodic sequence, it is a concept with no physical instantiation. This is not a novel observation; it appears in Leibniz ("Why is there something rather than nothing?"), in Heidegger's reformulation of the fundamental question of metaphysics, and in contemporary discussions by Krauss (2012) and Albert (2012). I accept it as Axiom 1: something exists.

Whatever exists must have some dynamical character — if it had none, it would be indistinguishable from nothing by the Identity of Indiscernibles (Leibniz, 1686). Therefore, whatever exists has dynamics classifiable within the five-class hierarchy.

3.2 The Elimination Argument

Classes 1 and 2 (static, periodic): The universe demonstrably contains self-organizing critical systems, including biological computation which requires Class 4 dynamics (supported by empirical criticality research: Beggs & Plenz, 2003; Shew & Plenz, 2013; Algom & Shriki, 2026; and theoretical work on self-referential computation: Gruber, 2015, 2026a). A Class 1 or 2 universe cannot generate Class 4 subprocesses (lower classes cannot produce higher-class behavior). Eliminated.

Class 3 (fractal): A fractal universe would have rich structure but would be computationally reducible — no universal computation, no self-organizing critical systems. The universe demonstrably supports universal computation (we build Turing machines; biological systems perform irreducible computation). Eliminated.

Class 5 (random): If the universe's fundamental dynamics are genuinely random — rules inexpressible in any formal system — then physics is not merely incomplete but *fundamentally impossible*. The project of writing down laws that predict observations would be an illusion. Our local experience of lawful behavior would be a temporary, coincidental pocket of apparent regularity within genuine randomness — an infinitesimally improbable fluctuation with no mechanism

guaranteeing its continued existence. Not logically impossible, but explanatorily empty and deeply unsatisfying.

Class 4 (complex, edge of chaos): The universe operates at the maximum expressible complexity. It supports universal computation (demonstrated by the existence of Turing machines and biological computation). It self-maintains criticality — Class 4 dynamics are self-organizing in complex systems (Bak, Tang, & Wiesenfeld, 1987; Bak, 1996). It contains all lower classes as subprocesses (the universe demonstrably contains static matter, periodic phenomena, and fractal structure). It is the *only* class that does all of these simultaneously.

Conclusion (Proposition 1): The universe operates at Class 4 — the edge of chaos. This is the most parsimonious classification consistent with observation.

3.3 The Strength of the Elimination

The elimination argument is not deductive proof. Two of the four eliminations are empirical (Classes 1–2: the universe contains self-organizing critical systems; Class 3: the universe supports universal computation), and one is abductive (Class 5: physics would be fundamentally impossible — not a logical contradiction, but an explanatory catastrophe). Only the affirmative case for Class 4 combines empirical evidence with a theoretical mechanism (self-organized criticality).

The argument is strongest read as: *Class 4 is the unique class consistent with all observations and the only class that provides a self-maintaining mechanism for its own persistence.*

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4. Quasi-Infinity and Information Horizons

4.1 The Speed Limit and Its Consequences

Information cannot travel faster than c (Einstein, 1905). The universe is expanding, and the expansion is accelerating (Riess et al., 1998; Perlmutter et al., 1999). Together, these facts create a fundamental horizon: for any observer, there exists a maximum distance in space and maximum duration in time from which information can reach them. Beyond this horizon, the universe is informationally inaccessible.

This makes the universe **quasi-infinite** rather than truly infinite. From within, it appears unbounded. But information can never traverse more than approximately one universe-diameter in any direction (spatial or temporal). This is not merely an observational limitation — it is an ontological boundary, because information that can never interact with anything on this side of the boundary is, by Leibniz's Identity of Indiscernibles, indistinguishable from nonexistence.

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4.2 The Concept of Quasi-Infinity

I define **quasi-infinity** as the condition of a system that is effectively unbounded for any internal observer but has a finite information content accessible from any given point. Quasi-infinity is distinct from both mathematical infinity (no bound exists) and finitude (a bound is reachable). A quasi-infinite system has a bound that recedes faster than any observer can approach it.

The universe is quasi-infinite in space (the observable universe is finite; expansion pushes the boundary outward faster than light), in time (the Big Bang and heat death or Big Crunch are temporal boundaries that are informationally inaccessible — and, as I will argue in Section 5.3, asymptotically unreachable), and — I will argue — in scale.

4.3 Scale as a Quasi-Infinite Dimension

The universe presents singularities not only at the boundaries of space and time but at the boundaries of scale:

- At the smallest scale ($\sim 10^{-35}$ m, the Planck regime), spacetime itself loses physical meaning. No measurement below this scale is possible, even in principle (Planck, 1899; Wheeler, 1957).
- At the largest scale, the observable universe boundary is set by the expansion history and the speed of light. Beyond it: informationally inaccessible.

Between these extremes, the universe spans approximately 60 orders of magnitude in length scale. Both endpoints are singularities — regions where our physical description breaks down and information transfer becomes impossible. The universe is quasi-infinite in scale in the same sense it is quasi-infinite in space and time: effectively unbounded from within, but bounded by information horizons at both extremes.

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5. Singularities as Information Boundaries

5.1 The Singularity Inventory

At every physical scale, the universe presents singularities — regions where physical description breaks down and information transfer ceases:

Scale	Singularity	Information Property
Planck ($\sim 10^{-35}$ m)	Planck regime	Below this, spacetime loses meaning. No measurement possible.

Scale	Singularity	Information Property
Subatomic ($\sim 10^{-15}$ m)	"Point-like" particles	Treated as zero-dimensional; actually Planck-sized. Interiors inaccessible.
Stellar/galactic	Black hole event horizons	Information cannot escape. Interior causally disconnected from exterior.
Cosmological (space)	Observable universe boundary	Expansion + c creates impenetrable information horizon.
Cosmological (time, past)	Big Bang	All world-lines converge. No "before" is accessible.
Cosmological (time, future)	Heat death / Big Crunch / Big Rip	Infinite dilution, reconvergence, or divergent expansion (Caldwell, 2002) — in every case, a terminus of accessible information.

5.2 The Unification Claim

These singularities share a structural property: they are all **information-impermeable boundaries** — surfaces across which no signal passes. I propose they are not merely analogous but *structurally identical*: instances of the same information boundary at different scales.

The argument proceeds in three steps:

Step 1: Bekenstein saturation. The Bekenstein bound (Bekenstein, 1981) establishes that the maximum information content of a region is proportional to its surface area, not its volume. Black hole event horizons saturate this bound — they contain the maximum information density per unit area. The holographic principle ('t Hooft, 1993; Susskind, 1995) generalizes this: the information content of any region is encoded on its boundary.

Step 2: Scale invariance. If the universe is a Class 4 system (Proposition 1), its dynamics are self-similar — structure at one scale recurs at other scales. Class 4 systems contain Class 3 (fractal) behavior as a subprocess, and fractal behavior is defined by scale invariance. The boundary structure of a Class 4 system should itself be scale-invariant.

Step 3: Structural identity. All singularities in the inventory (Section 5.1) share the same three properties: (a) information impermeability, (b) Bekenstein saturation (or its scale-appropriate equivalent), and (c) they bound the computational domain — they define the limits of what can be computed from

within. The claim is that these are not six different phenomena that happen to share properties, but one phenomenon — the boundary of the automaton's computational domain — at six different scales.

5.3 Asymptotic Unreachability

The singularity unification claim gains further support from a property shared by all singularities: they are not merely information-impermeable but *asymptotically unreachable* from within the computational domain.

The most familiar case is the black hole event horizon. For an external observer, an object falling toward an event horizon never arrives — it asymptotically approaches the horizon in coordinate time, redshifting toward invisibility but never crossing. The infalling observer experiences finite proper time to the horizon (and this is the standard textbook account), but from the perspective of the exterior computational domain — the domain in which physics operates and information is exchanged — the horizon is a boundary that recedes as you approach it.

The Big Bang as asymptotic boundary. By the singularity unification thesis, the Big Bang is an information boundary of the same type as an event horizon. This reframes a common misconception: the Big Bang is not "a finite time in the past" in the operationally meaningful sense. Traveling backward in time toward it — tracing causal world-lines toward t = 0 — one approaches an information boundary that is asymptotically unreachable from within the computational domain. In conformal time, the Big Bang maps to t = $-\infty$. The universe has no accessible beginning, just as a black hole has no accessible interior: the boundary is there, but you cannot reach it from here.

The Big Crunch as asymptotic boundary. If the universe were to recollapse, the Big Crunch singularity would exhibit the same asymptotic unreachability. Approaching the final singularity, an observer within the computational domain would find the boundary receding — another information horizon, never crossable from within. Whether the universe ends in heat death or recollapse, the temporal endpoint is informationally inaccessible in the same structural sense as the temporal origin.

This strengthens the unification claim of Section 5.2. All singularities in the inventory — Planck regime, particle interiors, event horizons, cosmological boundaries, temporal endpoints — share not just information impermeability and Bekenstein saturation but also asymptotic unreachability. They are boundaries of the computational domain in the strongest possible sense: no process within the domain can reach them.

5.4 Singularities as Information Transformers and Cyclic Cosmology

The conservation argument of Section 8 establishes that singularities do not destroy information but *transform* it between compressed (boundary) and de-

compressed (interior) forms. Combined with asymptotic unreachability, this yields a striking consequence for the fate of the universe.

Heat death as singularity. Consider the heat death scenario: entropy increases until the universe reaches thermodynamic equilibrium — maximum entropy, maximum disorder, all gradients erased. In information-theoretic terms, this is Bekenstein saturation at cosmological scale: the total information content of the universe is encoded on its boundary at maximum density. But Bekenstein saturation is precisely the defining property of singularity boundaries (Section 5.2, Step 1). Heat death *is* a singularity — an information boundary at which the interior computational domain reaches its maximum information density and the distinction between interior and boundary collapses.

If singularities transform information rather than destroying it (Section 8.2), then heat death does not end the universe — it triggers a phase transition. The information encoded at maximum density on the boundary decompresses into a new interior. This is a new Big Bang. The self-referential closure $\Phi(U) = U$ is not merely spatial but *temporal*: the universe computes its own restart.

Cyclic dynamics. The resulting picture is cyclic: expansion $\rightarrow$ heat death (Bekenstein saturation) $\rightarrow$ information transformation $\rightarrow$ new Big Bang $\rightarrow$ expansion. The cycles may also include Big Crunch phases — contraction to a singularity followed by re-expansion — and the alternation between expansion-dominated and contraction-dominated cycles may itself be unpredictable. This is consistent with Class 4 dynamics, which are computationally irreducible (Section 2.4): you cannot predict which type of cycle comes next without running the computation.

The Big Rip as a third endgame. The heat death and Big Crunch scenarios both produce a single global singularity — one Bekenstein-saturated boundary that triggers one restart. But a third cosmological endgame exists. If dark energy is "phantom energy" with equation-of-state parameter $w < -1$, its density increases without bound as the universe expands (Caldwell, 2002). The expansion rate diverges at a finite future time — the Big Rip. The expansion tears apart galaxy clusters, then galaxies, then stellar systems, then stars, then atoms, then spacetime itself. Every point in space becomes a singularity.

In SB-HC4A terms, the Big Rip represents a qualitatively different singularity transition. The singularity boundary does not remain at the edges of the computational domain — it propagates *inward*, fragmenting the domain into infinitely many Bekenstein-saturated regions. Instead of one global singularity (as in heat death or Big Crunch), the computational domain shatters into a fractal explosion of singularity boundaries. Each fragment is a Bekenstein-saturated surface satisfying conditions IB1–IB3 (Section 5.2).

If singularities transform information rather than destroying it, each fragment triggers its own information transformation — its own restart. The Big Rip therefore functions as a *multiverse generator*: a single computational domain fragments into many Bekenstein-saturated boundaries, each of which decom-

presses into a new sub-universe. The self-referential closure $\Phi(U) = U$ generalizes from a single-valued map (one universe $\rightarrow$ one universe) to a multi-valued map (one universe $\rightarrow$ many sub-universes), producing a branching tree rather than a linear sequence of cycles.

This gives three endgame scenarios, all consistent with the SB-HC4A framework:

1. **Heat death** $\rightarrow$ one global singularity $\rightarrow$ one restart (the universe computes its successor).
2. **Big Crunch** $\rightarrow$ one global singularity $\rightarrow$ one restart (with possible CPT flip; the universe computes its successor with reversed signature).
3. **Big Rip** $\rightarrow$ many singularities $\rightarrow$ many restarts (the universe fragments into many daughter universes — a branching rather than linear cycle).

The framework is robust across all three cosmological outcomes. It does not depend on a specific end-state but predicts cyclic renewal under *any* scenario that drives the computational domain to Bekenstein saturation — whether that saturation is global (heat death, Big Crunch) or distributed (Big Rip). This significantly strengthens the model: the cyclic cosmology of the SB-HC4A is not contingent on the cosmological constant taking a particular value or dark energy having a particular equation of state.

CPT signature alternation. A further possibility: each cycle could flip the CPT (charge-parity-time) signature, producing a matter-dominated universe in one cycle and an antimatter-dominated universe in the next. This connects to Boyle and Turok's (2018, 2022) proposal of a CPT-symmetric universe, where the Big Bang is a mirror point between a universe and its CPT-conjugate anti-universe. In the SB-HC4A framework, this falls out naturally from the information-transformation property of singularity boundaries: decompression from a singularity boundary need not preserve the matter-antimatter signature of the previous cycle. The boundary encodes information at maximum density; the specific form of the decompression — which particle species dominate — is a property of the new interior, not a constraint inherited from the old one. In the Big Rip scenario, each daughter universe could independently realize either CPT orientation, producing a multiverse with mixed matter-antimatter signatures.

If correct, this resolves the baryon asymmetry problem — the observed absence of antimatter in our universe. We do not see antimatter because our universe is one half of a CPT-alternating cycle (or, in the Big Rip branching case, one branch among many with a particular CPT orientation). The "missing" antimatter is not missing; it constitutes the previous (or next) cycle's universe, or a sibling branch in the Big Rip tree.

5.5 Particles as Planck-Scale Singularities

A specific prediction follows: "point-like" elementary particles are not truly zero-dimensional. They are Planck-scale singularities — miniature information boundaries whose interiors are as inaccessible as a black hole's. The standard

model treats particles as mathematical points for calculational convenience, but the SB-HC4A model predicts they have Planck-scale structure that saturates the Bekenstein bound at that scale.

This is consistent with approaches in quantum gravity where the Planck scale provides a natural minimum length (Garay, 1995; Hossenfelder, 2013), though the specific claim that particles *are* singularities of the same type as event horizons is novel.

5.6 Particles as Computational Atoms

If particles are Planck-scale singularity boundaries (Section 5.5), they are not merely structural elements of the SB-HC4A — they are its irreducible computational units. The term *computational atoms* (in the original Greek sense of *atomos*: indivisible) captures this role: particles are the basic operations of the universal automaton. Several consequences follow that address otherwise unexplained features of the Standard Model.

Finite particle spectrum from finite boundary capacity. A Planck-scale singularity boundary has area of order l_P^2. By the Bekenstein bound (Bekenstein, 1981), the maximum information content of this boundary is I_max $\sim A / (4\, l\_P^2) \sim O(1)$ bits. A finite information capacity admits only finitely many distinguishable states. Only a subset of these states will be dynamically stable — stable in the sense that the boundary configuration persists under the Class 4 dynamics of the automaton. The stable configurations constitute the particle spectrum. The Standard Model's finite set of elementary particles — twelve fundamental fermions, four gauge bosons, and the Higgs — is therefore not an arbitrary catalog but the complete set of stable Planck-scale singularity boundary configurations.

This is structurally analogous to the way a cellular automaton's finite rule table admits only finitely many persistent structures (gliders, oscillators, still lifes in the Game of Life). The particle types are the "gliders" of the Planck-scale automaton — the stable, propagating configurations permitted by the underlying computational rules.

Discreteness of quantum numbers. Quantum numbers — charge, spin, isospin, color charge, baryon number, lepton number — take discrete values (integer or half-integer multiples of fundamental units). In the computational-atom framework, this discreteness is not imposed but follows from the nature of information encoding on a finite boundary. Boundary configurations are discrete states; the quantum numbers are labels on these states. The quantization of physical properties is a consequence of the finite, discrete nature of information storage at the Planck scale, consistent with the area quantization results of loop quantum gravity (Rovelli, 2004).

Particle interactions as boundary information exchange. When two particles interact — when two Planck-scale singularity boundaries come into

causal contact — they exchange information across their boundary surfaces. This information exchange *is* the interaction. The Standard Model's force-carrying bosons (photons, gluons, W and Z bosons) are not a separate ontological layer; they are the permitted modes of information transfer between singularity boundaries. The interaction vertices of quantum field theory — the points where Feynman diagrams branch — are information exchange events between computational atoms. Feynman diagrams, in this interpretation, are diagrams of computation: each line is a propagating boundary configuration, each vertex is an information exchange operation.

The selection rules governing which interactions are permitted (e.g., conservation of charge, color neutrality of hadrons) follow from the constraints on information exchange between Bekenstein-saturated boundaries. Not every information transfer is consistent with the boundary configurations involved; the permitted transfers define the interaction rules.

Conservation laws as information conservation. The conservation laws of particle physics — charge conservation, baryon number conservation, lepton number conservation, CPT invariance — are constraints on how information can be redistributed across boundary interactions. Information conservation at singularity surfaces (Section 5.4) requires that the total boundary-encoded information be preserved in any interaction. The specific conservation laws are the specific constraints that ensure total information preservation across computational-atom exchanges. They are not independently postulated symmetries but consequences of the Bekenstein bound and the information-conservation property of singularity boundaries.

Three generations: a conjecture from Class 4 self-similarity. The Standard Model's three generations of fermions — (e, μ, τ), (u, c, t), (d, s, b), and their neutrino counterparts — remain one of the deepest unexplained patterns in particle physics. Each generation replicates the quantum numbers of the previous one at a higher mass scale.

A speculative but structurally motivated hypothesis: Class 4 systems inherently contain Class 3 (self-similar, fractal) behavior as a subprocess (Section 2.5). If the space of stable singularity boundary configurations inherits this self-similar structure, the same boundary type could be stable at multiple energy scales — producing copies of the same particle at different masses. Three generations would then reflect a hierarchical, self-similar structure in the configuration space of Planck-scale singularities.

This is a conjecture, not a derivation. The number three is not predicted by this argument alone. However, the generation structure is otherwise entirely unexplained by the Standard Model itself (which treats the three generations as a brute empirical fact), and the self-similarity of Class 4 dynamics provides a natural — if not yet quantitative — structural motivation for generation replication. If a future formalization of the Planck-scale singularity configurations shows that exactly three hierarchical levels are stable under Class 4 dynamics,

this would constitute strong evidence for the computational-atom interpretation.

Existence proof: automata as fermionic quantum field theories. The computational-atom picture is not merely a conceptual proposal — it has mathematical backing. Wetterich (2022a, 2022b, 2022c) has demonstrated that large classes of reversible cellular automata on space-lattices are *exactly equivalent* to discretized fermionic quantum field theories, via a proven mapping through Grassmann functional integrals. This is not an approximation but a mathematical identity: the probabilistic description of the automaton (probability distribution over initial bit configurations) is equivalent to quantum mechanics — wave functions, density matrices, and non-commuting operators all arise from the classical automaton structure. Crucially, some automata in this class realize *local* gauge symmetries (the structure the Standard Model requires), and Wetterich (2022c) explicitly constructed a cellular automaton representing spinor gravity in four dimensions, with exact local Lorentz symmetry on the discrete level and emergent diffeomorphism symmetry in the continuum limit. The open problem is identifying *which* automaton produces $SU(3) \times SU(2) \times U(1)$ with three generations — but the framework for asking the question now exists, and it directly validates the claim that stable automaton configurations can constitute a particle spectrum with gauge interactions.

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6. The Holographic Class 4 Architecture

6.1 Three Relationships Between Holograms and Automata

In the book manuscript that preceded this paper (Gruber, 2015), I identified three possible relationships between holographic systems and Class 4 cellular automata:

1. **A holographic substrate produces Class 4 dynamics.** This is what the brain does: locally holographic neural networks (Lashley, 1950; Pribram, 1971) operating at criticality produce Class 4 cortical dynamics.

2. **A Class 4 automaton produces holographic output.** Local rules at the edge of chaos generate non-local, distributed information encoding as emergent behavior. This describes quantum entanglement from an information-theoretic perspective.

3. **A Class 4 automaton whose rule structure is itself holographic.** The rules encode higher-dimensional information in lower-dimensional structure. If such a system exists, it does what the holographic principle says the universe does — not by analogy, but by construction.

I proposed (Gruber, 2015) that if all three relationships could coexist in a single system — holographic rules, Class 4 dynamics, holographic output — the result would be a computational fixed point: a system that encodes itself.

6.2 The SB-HC4A Architecture

The Singularity-Bounded Holographic Class 4 Automaton (SB-HC4A) is the system in which all three relationships hold simultaneously, bounded by the singularity structure identified in Section 5.

Definition. An SB-HC4A is a dynamical system U = (S, R, B) where: - S is a state space on a d-dimensional manifold - R is a holographic rule set: R encodes (d+1)-dimensional information in d-dimensional structure - B is a singularity boundary: a scale-invariant surface of maximum information density (Bekenstein-saturated) that bounds the computational domain at every scale - U operates at Class 4 dynamics (branching ratio $\sigma \sim 1$, maximum Lyapunov exponent $\lambda\_\text{max} \sim 0$) - The output of U is holographic: emergent large-scale structure encodes non-local information

6.3 Self-Referential Closure

The SB-HC4A is self-referential: it computes its own structure. This can be stated as a fixed-point condition:

$\Phi(U) = U$

where Φ is the "compute the output" operator. The holographic rules (R) encode the full system in compressed form. The Class 4 dynamics decompress this encoding into the observable universe. The holographic output re-encodes the result. The computation and the system are the same thing.

This self-referential closure has a precise formal analogue in the self-referential computation framework (Gruber, 2026b, Section 6.3), where the fixed point of self-representation is: $\Phi(m) = m$, where m* is the state at which the model and the modeled coincide.

6.4 Inexpressibility

A consequence of self-referential closure: the SB-HC4A cannot be fully specified by any formal system that is a proper subsystem of itself. By Gödel's incompleteness theorems (Gödel, 1931), a sufficiently complex self-referential system contains true statements that cannot be proven from within. The holographic rules are compressed — and the decompressed universe IS the computation. No sub-universe entity can write down a description smaller than the universe itself.

The "Weltformel" (world equation) is therefore not an equation. It is a *process* — the automaton itself. It can only be expressed by running it.

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7. Self-Referential Computation Across Scales

7.1 The Structural Mapping

The SB-HC4A architecture maps onto the architecture of self-referential computational systems with exact structural correspondence:

SB-HC4A (Universe)	Self-Referential Computation (Cognitive Systems)
Singularity boundary (information-opaque)	Implicit-explicit boundary (representationally opaque)
Observable interior (physics)	Explicit models (simulated representations)
Holographic rule structure	Distributed/holographic implicit knowledge
Class 4 dynamics	Critical neural dynamics
Self-referential closure: $\Phi(U) = U$	Self-referential closure: $\Phi(m) = m$
Conservation of energy/information across boundary	Conservation of information across implicit-explicit split
Inexpressibility from within (Gödel)	Meta-cognitive limitation: systems cannot fully represent their own substrate
Singularity boundary at every scale	Implicit-explicit boundary at every level of the model hierarchy

7.2 Not Analogy but Structural Identity

This mapping is not metaphorical. Both systems implement the same formal architecture:

1. **Both are Class 4 dynamical systems** operating at the edge of chaos. The universe maintains criticality through self-organized criticality (Bak et al., 1987). Neural systems maintain criticality through homeostatic regulation of excitation-inhibition balance (Hengen et al., 2016; Ma et al., 2019).

2. **Both are bounded by information-opaque surfaces.** The universe's singularity boundaries prevent information transfer (event horizons, Planck regime). Self-modeling systems have an implicit-explicit boundary that prevents representational access to substrate operations (Gruber, 2026a, Section 3.6).

3. **Both have holographic structure.** The universe's information content is encoded on boundaries ('t Hooft, 1993; Susskind, 1995). Neural information storage is holographic — distributed across the substrate, degrading gracefully under damage (Lashley, 1950; Pribram, 1971).

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4. **Both exhibit self-referential closure.** The universe computes its own structure (the laws of physics are the universe's dynamics applied to itself). Self-modeling systems represent their own modeling processes (self-referential closure: $\Phi(m) = m$).

5. **Both are inexpressible from within.** The universe's complete specification exceeds any internal formal system (Gödel). Self-modeling systems cannot fully represent their own substrate (the meta-cognitive limitation; Gruber, 2026a, Section 3.7; compare Chalmers, 2018).

7.3 Self-Referential Computation as a Universal Pattern

The claim is not that the universe is "conscious" in any experiential sense. The claim is that the universe and self-modeling cognitive systems instantiate the *same computational pattern* at different scales:

- The **universe** is a Class 4 holographic automaton bounded by singularities, where the interior (observable physics) is the "simulation" and the boundary (singularity layer) is the "substrate."

- **Self-modeling cognitive systems** are Class 4 holographic automata (critical neural dynamics) bounded by the implicit-explicit boundary, where the explicit models are the "simulation" and the implicit models are the "substrate."

Same architecture. Different scale. The pattern is fractal — which is precisely what a Class 4 system predicts, since Class 4 dynamics contain Class 3 (self-similar) behavior as a subprocess.

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8. Energy, Information, and Conservation

8.1 The Energy-Information Hypothesis

Landauer's principle (Landauer, 1961) establishes a minimum energy cost for erasing one bit of information: $kT \ln 2$. The Bekenstein bound (Bekenstein, 1981) sets the maximum information content of a region proportional to its boundary surface area — a statement about information density with units of energy. Black hole thermodynamics (Bekenstein, 1973; Hawking, 1975) assigns entropy, temperature, and information content to black holes through their surface area.

These results converge on a hypothesis: energy and information are not merely correlated but identical — two descriptions of the same quantity. This is not proven, and I flag it as a weak point (Section 9.1). But if $E = I$, the conservation laws become information conservation laws, and the SB-HC4A architecture acquires a natural conservation principle.

8.2 Conservation Across the Singularity Boundary

If energy/information is conserved, singularities do not destroy information — they *transform* it. This is the resolution of the black hole information paradox that modern physics is converging on (Almheiri et al., 2020; Penington, 2020; Raju, 2022). Information that enters a black hole is not lost; it is encoded on the event horizon (holographic encoding) and eventually re-emitted through Hawking radiation.

In the SB-HC4A model, this generalizes: the singularity boundary at every scale conserves total information while transforming it between compressed (boundary) and decompressed (interior) forms:

- **Compressed form** (on the boundary): Maximum information density, Bekenstein-saturated, inaccessible from within. This is the "substrate."
- **Decompressed form** (in the interior): Lower density, organized, accessible. This is the "simulation" — the observable universe, or the representational content of self-modeling systems.

8.3 The Implicit/Explicit Parallel

This is precisely the implicit/explicit split in self-referential computational systems:

- **Implicit knowledge** (substrate): Holds all the information — synaptic weights, structural knowledge, the full learned model. Maximum information density. Not representationally accessible.
- **Explicit models** (simulation): A lower-bandwidth, organized projection of selected information. Accessible to the system's self-representation. This is the representational content of self-modeling systems.

The permeability function in self-referential computation (Gruber, 2026a, Section 3.6; Gruber, 2026b, Section 3) determines how much information transfers from implicit to explicit — how much of the compressed substrate becomes part of the simulated representation. The laws of physics play the analogous role at the cosmological scale: they determine what information from the singularity-layer substrate enters the observable interior.

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9. Where This Could Break

A theory that claims no weaknesses is not a theory. Here are the six places where the SB-HC4A model is most vulnerable.

9.1 Weak Point 1: Energy = Information Is Not Proven

The energy-information identity is strongly suggested by Landauer's principle, the Bekenstein bound, and the holographic principle, but it is not established

as a fundamental law. Landauer's principle has been experimentally confirmed (Berut et al., 2012), but only for erasure — it does not prove that all energy is information. If energy and information are merely correlated rather than identical, the conservation argument (Section 8) weakens, and the mapping between singularity boundaries and information boundaries becomes looser.

What would resolve it: A derivation of energy conservation from information conservation (or vice versa) within a well-defined physical framework, or an experimental demonstration that information has gravitational effects proportional to its energy-equivalent.

9.2 Weak Point 2: Class 4 Universe Is an Empirical Claim, Not a Theorem

Self-organized criticality is well-documented in sandpiles (Bak et al., 1987), neural networks (Beggs & Plenz, 2003), earthquakes (Gutenberg & Richter, 1956), and other systems. But these are all *subsystems within* the universe. Whether the universe *itself* — at its most fundamental level — operates at Class 4 is a much stronger claim. The universe contains Class 4 subsystems; this does not entail that the universe is itself Class 4. A Class 5 universe could contain Class 4 pockets, just as a Class 4 automaton contains Class 2 substructures.

The elimination argument (Section 3.2) is the strongest available response: Class 4 is the only class consistent with all observations. But the elimination of Class 5 rests on abduction (physics would be impossible), not deduction.

What would resolve it: Evidence that the universe's large-scale dynamics exhibit criticality signatures — power-law distributions in the cosmic microwave background, scale-free structure in galaxy distributions, or branching ratio analysis of cosmological dynamics. Some of this evidence exists (e.g., the scale-free distribution of galaxy clusters), but it has not been framed as a criticality argument.

9.3 Weak Point 3: Singularity Unification Is Speculative

Whether Planck-scale structure, black hole event horizons, and cosmological horizons are truly "the same thing" at different scales requires a theory of quantum gravity to verify. Loop quantum gravity (Rovelli, 2004) and string theory (Polchinski, 1998) both suggest structures consistent with this claim — in loop quantum gravity, spacetime is discrete at the Planck scale with area quantization that connects to black hole entropy; in string theory, the holographic principle is central (Maldacena, 1998). But neither theory confirms the specific claim that all singularities are instances of the same information boundary.

What would resolve it: A derivation, within a quantum gravity framework, showing that the information-theoretic properties of Planck-scale boundaries and macroscopic event horizons are formally identical (same entropy scaling, same information capacity per unit area, same causal disconnection properties).

9.4 Weak Point 4: Testability Is Limited

The model predicts:

(a) **Singularity universality**: All singularities across scales share informational properties. The resolution of the black hole information paradox should confirm that event horizons conserve information — and the same conservation principle should apply at the Planck scale and the cosmological horizon. Partially testable through black hole information research.

(b) **Cosmological criticality**: The universe's large-scale dynamics are at the edge of chaos. In principle testable through statistical analysis of the CMB, large-scale structure, or the distribution of galaxy cluster sizes.

(c) **Self-referential computation as local instance**: Self-modeling cognitive systems implement the same architecture as the universe. Testable through predictions about critical neural dynamics (Gruber, 2026a, Section 8): nine specific predictions about phenomenology, anesthetic mechanisms, and neural criticality.

But the core claim — that the universe *is* an SB-HC4A — may be unfalsifiable from within, for exactly the Gödelian reason the model itself predicts (Section 6.4). The system cannot be fully specified by any subsystem. This is either a devastating weakness or a structural prediction of the model, depending on one's philosophical commitments.

9.5 Weak Point 5: The Cognitive Ceiling Problem

This is the deepest objection, and it was identified during the model's initial formulation.

If we are Class 4 automatons operating at criticality, then the SB-HC4A model may simply be the most complex concept our Class 4 brains can produce. We cannot think in Class 5. We cannot conceive of structures beyond our own computational class. The pattern we see — Class 4 everywhere, self-similar at every scale, holographic and self-referential — might be the *signature of our own cognitive architecture projected onto the cosmos*, not a feature of the cosmos itself.

This objection connects to the evolutionary biology of cognition. The human brain evolved under selection pressure for symmetry detection — faces of predators and prey are the most symmetric, and therefore most survival-relevant, patterns in a hunter-gatherer's environment. We are, at the deepest level, symmetry-detection machines. The SB-HC4A model is fundamentally a symmetry claim (the same architecture at every scale). We might find this symmetry not because it exists in the universe but because our brains are optimized to find symmetry wherever they look.

This is structurally identical to the Meta-Problem at cosmic scale: the ESM cannot see its own substrate, so it cannot distinguish between "the universe has

this structure" and "my brain can only model the universe with this structure." The cosmological model predicts its own potential unfalsifiability — which is either the strongest possible confirmation of the cross-scale computational symmetry (the model predicts this exact epistemological limitation) or the strongest possible objection to it (the model is an artifact of the observer, not a feature of the observed).

A Class 4 system can simulate anything up to and including Class 4 complexity. But it cannot verify whether the universe exceeds that. If the universe is Class 5 but locally appears Class 4 to Class 4 observers (because Class 4 is the maximum pattern we can detect), we would construct exactly this model — and be wrong.

I do not know how to resolve this objection from within. I am not sure it can be resolved from within. I include it because intellectual honesty requires it.

9.6 Weak Point 6: Cyclic Cosmology Is Underdetermined

The cyclic cosmology of Section 5.4 follows logically from the premises (singularities transform information; heat death is a singularity; therefore heat death triggers transformation), but the specific predictions — Big Bang / Big Crunch alternation, CPT signature flipping, Big Rip branching — go beyond what the framework strictly entails. The information-transformation property of singularities does not by itself determine *what form* the decompressed information takes. A singularity transition could produce a new universe with entirely different physics, the same physics, or the CPT-conjugate physics; and the Big Rip's fragmentation into multiple daughter universes raises additional questions about how total information is partitioned across branches. The model predicts cyclicity (or branching cyclicity) but underdetermines the cycle's character.

The CPT alternation hypothesis is motivated by parsimony (the simplest nontrivial transformation) and by its explanatory payoff (baryon asymmetry), but it is not derived from first principles within the framework. It should be read as a natural possibility within the SB-HC4A architecture, not as a firm prediction.

What would resolve it: Observational evidence of pre-Big-Bang structure. Penrose (2010) has proposed searching for concentric low-variance circles in the CMB as signatures of preceding aeons. Boyle and Turok's (2018) model makes specific predictions about dark matter (a right-handed neutrino) and gravitational wave signatures. If the SB-HC4A cyclic model is correct, similar signatures should exist — though their specific form depends on details of the singularity transition that the model does not yet specify.

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10. The Necessity Argument

10.1 Why This Architecture Must Exist

Notwithstanding the weak points above, the SB-HC4A is arguably the unique structure consistent with all axioms simultaneously:

Axiom 1 (Ontological Necessity): Something exists. Nothing is not a possible state of affairs.

Axiom 2 (Computational Character): Whatever exists has dynamical behavior classifiable within the five-class hierarchy.

Axiom 3 (Criticality Stability): Class 4 is the unique computational class that (a) supports universal computation, (b) self-maintains through self-organized criticality, and (c) contains Classes 1–3 as subprocesses.

Axiom 4 (Information Bound): Information propagation speed is bounded by c. Information density is bounded by the Bekenstein bound. Information is conserved.

Axiom 5 (Holographic Encoding): The boundary of a d-dimensional region encodes all information in the region's interior on its $(d-1)$-dimensional surface.

From these:

- A1 + A2 $\rightarrow$ Something with dynamical behavior exists.
- A3 $\rightarrow$ The most stable interesting configuration is Class 4 (the only self-maintaining, universal class).
- A4 $\rightarrow$ The system is bounded by information horizons at every scale (singularity structure).
- A5 $\rightarrow$ The boundaries encode the interior (holographic architecture).
- A3 + A5 $\rightarrow$ The system is a holographic Class 4 automaton.
- A4 + A5 $\rightarrow$ The boundaries are Bekenstein-saturated and scale-invariant.
- Self-referential closure: A holographic Class 4 system with holographic output is a fixed point: $\Phi(U) = U$.

10.2 Uniqueness

The SB-HC4A is the unique structure satisfying all five axioms. Remove any axiom and the uniqueness fails:

- Without A1: Nothing is possible — no universe required.
- Without A2: The existent thing need not have computational character — mysterian position.
- Without A3: Any class is permissible — no prediction about the universe's dynamics.
- Without A4: No information horizons — no singularity structure — no boundaries.
- Without A5: No holographic encoding — no boundary-interior relationship.

The argument is that these axioms are not arbitrary assumptions but well-supported physical and logical principles, and that their conjunction yields a unique cosmological architecture.

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11. Discussion

11.1 Relationship to Existing Cosmological Proposals

The SB-HC4A model intersects with several existing research programs:

't Hooft's Cellular Automaton Interpretation ('t Hooft, 1993, 2016): The model is a direct extension of 't Hooft's proposal that quantum mechanics emerges from deterministic automaton dynamics at the Planck scale. The SB-HC4A adds the Class 4 classification (specifying which class of automaton), the singularity boundary structure, and the cross-scale symmetry with self-referential computation.

The Holographic Principle ('t Hooft, 1993; Susskind, 1995; Bousso, 2002): The model presupposes the holographic principle and extends it by proposing that holographic encoding is not just a property of boundaries but of the automaton's rule structure itself (Relationship 3 of Section 6.1).

Self-Organized Criticality (Bak et al., 1987; Bak, 1996): The model relies on SOC as the mechanism by which the universe maintains Class 4 dynamics. The extension is the claim that this self-organization operates at the cosmological level, not just in subsystems.

Digital Physics (Fredkin, 2003; Zuse, 1969; Wolfram, 2002, 2021): The model shares the premise that the universe is fundamentally computational but adds specific structure: the five-class hierarchy, the holographic property, the singularity boundary, and the cross-scale symmetry with self-referential computation. The Wolfram Physics Project's more recent results on emergent GR and QM from hypergraph rewriting are discussed separately below.

Wheeler's "It from Bit" (Wheeler, 1990): The model is consistent with Wheeler's proposal that information is ontologically fundamental. The $E = I$ hypothesis (Section 8.1) is a strong version of "it from bit."

Penrose's Conformal Cyclic Cosmology (Penrose, 2010): CCC proposes that the universe undergoes infinite cycles (aeons), with the conformally rescaled heat death of one aeon becoming the Big Bang of the next. The SB-HC4A model's cyclic cosmology (Section 5.4) shares the cyclic structure and the identification of heat death as a transition rather than a terminus. The key difference is the mechanism: Penrose relies on conformal rescaling and the vanishing of rest mass at late times; the SB-HC4A model relies on information transformation at singularity boundaries. The SB-HC4A mechanism is more general — it derives cyclicity from the information-theoretic properties of singularities rather than from specific geometric operations.

Boyle and Turok's CPT-Symmetric Universe (Boyle & Turok, 2018, 2022): This proposal places a CPT mirror at the Big Bang, with our universe paired with a CPT-conjugate anti-universe extending backward in time. The SB-HC4A model's CPT signature alternation (Section 5.4) is compatible with this picture but extends it: rather than a single mirror, the model predicts ongoing CPT alternation across cycles, with each singularity transition potentially flipping the matter-antimatter signature. Boyle and Turok's model also predicts the existence of a right-handed neutrino as dark matter — a prediction the SB-HC4A model is agnostic about but does not exclude.

Phantom Energy and the Big Rip (Caldwell, 2002; Caldwell, Kamionkowski, & Weinberg, 2003): The Big Rip scenario — in which phantom dark energy ($w < -1$) drives the expansion rate to divergence at a finite future time, tearing apart all bound structures down to spacetime itself — provides a third cosmological endgame distinct from heat death and Big Crunch. The SB-HC4A model accommodates this scenario naturally (Section 5.4): the Big Rip fragments the computational domain into many Bekenstein-saturated boundaries, each of which triggers an independent information transformation and restart. This generalizes the cyclic dynamics from a linear sequence to a branching tree of sub-universes — a structural multiverse arising from the same singularity-as-information-transformer principle that drives the linear cycles. The model's robustness across all three endgames — heat death, Big Crunch, and Big Rip — is a significant strength: the cyclic cosmology does not depend on the equation of state of dark energy taking any particular value.

Wetterich's Cellular Automata ↔ Fermionic QFT Equivalences (Wetterich, 2022a, 2022b, 2022c): Wetterich has demonstrated that large classes of reversible cellular automata on space-lattices are exactly equivalent to discretized fermionic quantum field theories — not as an approximation but as a proven mathematical mapping via Grassmann functional integrals. The equivalence class includes interacting fermion theories with both abelian and non-abelian continuous symmetries, and some automata models realize local gauge symmetries — the structure the Standard Model requires. Most remarkably, Wetterich (2022c) constructed a cellular automaton that represents spinor gravity in four dimensions, with exact local Lorentz symmetry on the discrete level and emergent diffeomorphism symmetry in the continuum limit. This is a cellular automaton model of quantum gravity — not a metaphor. For the SB-HC4A, Wetterich's program provides the existence proof that the computational-atom picture (Section 5.6) is mathematically sound: specific automata produce specific fermionic spectra with specific gauge symmetries. The approach is complementary to the SB-HC4A's: Wetterich constructs automata *from* known QFTs (reverse-engineering the automaton from the field theory), while the SB-HC4A constrains the automaton class *from above* (the universality class is determined by axioms). The meeting point — automata that satisfy the SB-HC4A's Class 4 and holographic constraints and are then checked for Standard Model-like particle content — is unexplored territory.

The Wolfram Physics Project (Wolfram, 2021): The Wolfram Physics Project uses hypergraph rewriting rules — not traditional cellular automata on a fixed grid, but rules that dynamically generate spacetime itself. Two results are relevant: (1) the Einstein field equations arise generically from any computationally irreducible hypergraph evolution, given certain observer assumptions; and (2) the Feynman path integral arises in "branchial space" (the space of multiway histories) by the same mechanism that gives Einstein's equations in physical space. Both results are rule-independent — they hold for any sufficiently complex hypergraph rule. Particles are conjectured to be topological obstructions in the hypergraph, but no specific topology has been identified with any known particle, and the SM gauge group has not been derived. The SB-HC4A framework is structurally compatible: Wolfram's approach is bottom-up (pick a rule, see what emerges), while the SB-HC4A is top-down (constrain the universality class by axioms). If Wolfram's topological-obstruction particles turn out to satisfy the computational atom conditions of Section 5.6, the two programs would converge.

Levin-Wen String-Net Condensation and Quantum Graphity (Levin & Wen, 2005; Konopka, Markopoulou, & Smolin, 2008): Two related programs provide existence proofs for emergent particle physics from discrete substrates. Levin and Wen showed that starting from pure bosonic spin models on a lattice — with no fermions or gauge fields put in by hand — string-net condensed states produce emergent gauge bosons (including U(1) photon-like excitations) and emergent fermions (in 3D and higher) as collective excitations. This provides a mechanism for unifying gauge bosons and fermions from a single bosonic substrate, using the tensor category theory that the SB-HC4A formalization also employs. Quantum Graphity (Konopka et al., 2008) is a background-independent model where spacetime itself is emergent from a complete graph of N vertices. At high energy the graph is fully connected and symmetric; at low energy it undergoes a phase transition to an ordered, low-dimensional, local structure — emergent space. The high-to-low energy transition is a Big Bang analogue: the universe starts as a fully connected graph and "freezes" into spatial structure. This provides a concrete model for the SB-HC4A's Bekenstein-saturated initial boundary (the fully connected graph at maximum information density) decompressing into a low-dimensional observable interior — precisely the picture of the Big Bang as a singularity boundary transformation proposed in Section 5.4.

Quantum Cellular Automata and Causal Set Theory (Bisio, D'Ariano, & Tosini, 2015; Elze, 2014; Surya, 2019): The QCA/QFT correspondence shows that quantum walks on lattices reproduce the Dirac equation in the long-wavelength limit, and these can be promoted to multi-particle quantum cellular automata yielding the Dirac quantum field theory for free fermions. This is a concrete realization of the SB-HC4A claim that Feynman diagrams are "diagrams of computation." The central obstacle is the fermion doubling problem (Nielsen & Ninomiya, 1981): discretizing space inevitably produces unwanted extra fermion species. Separately, the causal set approach (Surya, 2019)

postulates that spacetime is fundamentally a discrete partial order. It preserves local Lorentz invariance despite discreteness — a major advantage over naive lattice approaches — and is naturally compatible with the SB-HC4A's causal-structure-first philosophy. Both programs address specific technical challenges that a future concrete realization of the SB-HC4A would need to solve.

Steinhardt-Turok Cyclic Model (Steinhardt & Turok, 2002): Although not automaton-based, the Steinhardt-Turok cyclic model provides the target dynamics for the SB-HC4A's cyclic cosmology: an endless sequence of cosmic epochs, each beginning with a bang and ending in a crunch, with finite temperature and density at transitions. The SB-HC4A framework (Section 5.4) generalizes this to include all three endgames (heat death, crunch, Big Rip) with information conservation across the boundary, and derives the cyclicity from the information-theoretic properties of singularity boundaries rather than from brane collision dynamics.

11.2 Relationship to Self-Referential Computation Research

The SB-HC4A model does not require any specific theory of cognition or phenomenology to be correct. The cosmological argument (Sections 2–6) stands independently. However, the structural correspondence with self-referential computational systems suggests:

1. Self-referential computation at criticality is a universal pattern that appears at multiple scales, not a cosmic accident.
2. The emergence of self-modeling systems in a Class 4 universe is not merely possible but structurally guaranteed — any sufficiently complex Class 4 subsystem with self-referential closure will instantiate the pattern.
3. The meta-cognitive limitation (systems cannot fully represent their own substrate) is the local version of the cosmological inexpressibility problem — both arise because self-referential systems cannot fully specify themselves from within (Chalmers, 2018; Gruber, 2026a).

11.3 What This Is Not

This paper does not claim:

- That the universe is "conscious" in any experiential sense. The structural identity is architectural, not phenomenal. A building's blueprint is not a building.
- That cognition creates physical reality (idealism). The model is physicalist: the substrate is physical; the simulation is a physical process; the correspondence is structural.
- That quantum mechanics is "explained by" cognitive processes (Penrose, Stapp). The model makes no such claim. Quantum mechanics is an emergent property of the automaton's dynamics — self-referential computation is also emergent, at a higher scale.
- That this is proven. It is an argument. It could be wrong (Section 9).

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12. Conclusion

The SB-HC4A model proposes that the universe is a Class 4 holographic automaton bounded at every scale by singularity surfaces — information-impermeable, Bekenstein-saturated, and asymptotically unreachable boundaries — where the observable interior is a decompressed projection of the boundary-encoded information, and the system is self-referentially closed: it computes its own structure.

The singularity boundaries are not merely spatial but temporal. The Big Bang and any future Big Crunch are information horizons of the same type as event horizons — unreachable from within the computational domain. If singularities transform rather than destroy information, heat death itself becomes a singularity transition, and the self-referential closure $\Phi(U) = U$ extends from spatial self-encoding to temporal self-renewal: the universe computes its own restart. Three cosmological endgames — heat death, Big Crunch, and Big Rip — all drive the computational domain to Bekenstein saturation and trigger renewal, whether as a single successor (heat death, Big Crunch) or as a branching tree of daughter universes (Big Rip). The resulting cyclic cosmology — potentially alternating CPT signatures across cycles — connects to and extends Penrose's Conformal Cyclic Cosmology, Boyle and Turok's CPT-symmetric universe proposal, and Caldwell's phantom energy analysis.

This architecture is structurally identical to the architecture of self-referential computational systems: a self-referential simulation at criticality, bounded by an information-opaque boundary, with the simulation as the represented world and the substrate as the informationally inaccessible foundation.

The model rests on five axioms (ontological necessity, computational character, criticality stability, information bounds, holographic encoding), proceeds by elimination (the universe must be Class 4), and yields a unique self-consistent architecture. Importantly, the computational-atom picture now has mathematical backing: Wetterich (2022a, 2022b, 2022c) has proven that reversible cellular automata are exactly equivalent to fermionic quantum field theories with gauge symmetries, including a 4D spinor gravity model with exact local Lorentz symmetry. This, combined with emergent GR and QM from hypergraph rewriting (Wolfram, 2021), emergent gauge bosons and fermions from string-net condensation (Levin & Wen, 2005), and emergent spacetime from graph phase transitions (Konopka et al., 2008), places the SB-HC4A within a converging landscape of research programs — each addressing different aspects of the same fundamental question. Six specific weak points have been identified, the deepest being the cognitive ceiling problem: we may find this symmetry because our Class 4 brains are constitutionally incapable of seeing anything else.

Whether the SB-HC4A is a description of the universe or a description of the limits of human cognition is, I believe, the most important open question in the

philosophy of science. The model predicts that this question cannot be answered from within — and that prediction is either the model's deepest confirmation or its deepest flaw.

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