Black Hole Singularities as Zero-Entropy States

Juha Meskanen

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Abstract

We investigate black hole singularities from an information-theoretic perspective. Under the principles established in Paper I [6], geometric spacetime and the execution trace of a computational simulation are two equivalent representations of the same underlying informational structure, with neither being more fundamental. Standard General Relativity cannot be evolved through singularity formation due to numerical divergences and the breakdown of the manifold description. However, the execution trace provides a complementary, well-behaved description that remains defined throughout collapse. We argue that the singularity is not a point of infinite curvature but a state of zero entropy state. Any mapping of zero entropy yields a single geometric object - a point. A zero entropy state is incapable of supporting microstructure, matter, or distinguishable geometry, and therefore is not of point of infinite curvature. The failure of GR is respresentational, not a break down of physics.

1 Introduction

The singularity theorems of Penrose and Hawking establish that gravitational collapse generically produces spacetime singularities — regions where curvature diverges and the classical manifold description breaks down [7, 4]. The standard interpretation is that singularities mark the boundary of applicability of General Relativity and that a theory of quantum gravity is required to describe what occurs there.

The present paper proposes a different interpretation. Geometric spacetime and the execution trace of a computational simulation are two representations of the same informational structure. This equivalence allows the singularity to be approached from the informational side even when the geometric description fails. The central question is not what the geometry does at the singularity — it diverges, by definition — but what the execution trace does. The answer, we find, is that the informational variety of the execution trace collapses into a trivial zero entropy state.

To rigorously isolate this collapse, we evaluate the spatial state under three distinct information-theoretic lenses: microscopic bitwise diversity, localized pattern redundancy via block structures, and structural resource costs via continuous spatial frequency spectra. This multi-metric spectrum reframes the singularity entirely. A zero-entropy, zero-complexity bitstring encodes a single, structureless state. Under any geometric decoding, a zero-entropy source resolves to a point of zero size. It cannot encode microstructures, particles, or stress-energy. The singularity is therefore not a point where physics breaks down but an informational state where physics becomes trivially simple: there is nothing there to be described.

Existing approaches to singularity regularisation — loop quantum gravity, string-theoretic fuzzballs, effective field theory cutoffs — introduce new physics at the Planck scale. The present approach requires no new physics. The regularisation is not imposed but derived from the informational structure of the collapse process itself.

The paper is structured as follows. Section 2 summarises the relevant results from Paper I [6]. Section 3 defines the execution trace, the geometric encoding, and the multi-metric complexity suite. Section 4 presents the numerical results for Schwarzschild, Advanced Unistructural (AU), Eddington-Finkelstein (EF), and Kerr geometries. Section 5 interprets the results and discusses their physical implications. Section 6 concludes.

2 Informational Equivalence of Geometry and Computation

The argument of this paper rests on the proposition established in Paper I [6], which we summarise here for completeness.

Corollary (Representational equivalence). The geometric description of a physical process and the computational description of its simulation are two representations of the same informational structure, with neither being more fundamental.

The representational equivalence is what licenses the approach of this paper. When the geometric description fails — as it does at the singularity — the computational description remains well-defined, and its properties can be read back as properties of the geometry.

3 Methods

3.1 Execution Trace

Let $\mathcal{M}$ denote the set of all memory locations in a deterministic computing system. A *machine state* $\mathcal{S} \in \mathcal{M}$ is a complete assignment of values to all memory elements. Let $\mathcal{P} = (I_1, I_2, \ldots, I_n)$ be a finite sequence of deterministic instructions, with $I_k : \mathcal{S} \to \mathcal{S}$. The *execution trace* $\mathcal{T}$ of program $\mathcal{P}$ is the ordered sequence of states

$$\mathcal{T} = (s_0, s_1, \ldots, s_n), \quad s_{k+1} = I_{k+1}(s_k).$$

The execution trace encodes all information about the simulated phenomenon. By the representational equivalence of Section 2, it encodes all information about the physical phenomenon as well. In practice, we focus on the *bitstring sub-trace*: the subsequence of memory states that encodes the spatial geometry of the simulated system.

3.2 Geometric Encoding

Let a geometric state at time t be encoded as a bitstring $b_t \in \{0,1\}^L$, representing the discretised positions of all particles in the simulated dust cloud. Let

$$\mathcal{C} = \{0,1\}^{3k}$$

be the space of three-dimensional configurations. Define the decoding map

$$f : \mathcal{C} \to \mathbb{Z}^3, \quad f(b) = (\phi(b_1), \phi(b_2), \phi(b_3)),$$

where $\phi : \{0,1\}^k \to \mathbb{Z}$ decodes fixed-length binary segments into integers via standard binary representation. Distinct bitstrings decode to distinct integer triples. Quantisation of continuous coordinates to fixed-width integers eliminates spurious entropy contributions from floating-point representation and ensures that the entropy of the bitstring faithfully reflects the geometric distinguishability of the encoded states.

3.3 The Informational Diagnostic Suite

To extract both macroscale pattern formation and microscale structural disorder during gravitational collapse, we evaluate the particle coordinate distribution using three complementary informational metrics.

3.3.1 Single-Bit Shannon Entropy

At each simulation timestep t, the full geometric state is mapped onto a vector of continuous positions, which are evaluated as a 1D spatial array of radii r_n or coordinate positions. To evaluate low-level bitwise diversity, this spatial state is scaled by an integer mapping constant $\alpha = 1000.0$ and parsed at the raw bit level. We compute the Shannon entropy of the empirical bit-frequency distribution:

$$H(b_t) = -p_0(t)\log_2 p_0(t) - p_1(t)\log_2 p_1(t),$$

where $p_0(t)$ and $p_1(t)$ are the global frequencies of zero- and one-bits across all parsed words at time t. This measures the fundamental distinguishable variety encoded in the machine representation.

3.3.2 Pattern Block Entropy

Because single-bit Shannon entropy treats bits as independent identically distributed variables, it can obscure localized correlations. We implement a spatial pattern variety metric by grouping the bitstream into consecutive sequences of fixed word size $n = 4$. The normalized block entropy is defined as:

$$H_n(b_t) = -\frac{1}{n}\sum_{i=1}^{2^n} P(\omega_i)\log_2 P(\omega_i),$$

where $P(\omega_i)$ is the empirical probability of occurrence of the i-th binary pattern word $\omega_i \in \{0,1\}^n$. Due to the fixed scaling properties inherent in binary integer transitions, $H_n(b_t)$ tracks tightly with $H(b_t)$, confirming a high degree of correlation between individual bit state changes and pattern distributions during spatial collapse.

3.3.3 Dynamic Spectral Complexity

To isolate multi-scale spatial organization from bulk coordinate scaling, we implement the continuous spatial rendering resource cost. Let $\bar{x}(t)$ denote the mean value of the N-particle spatial distribution $x_n(t)$ at time t. We isolate the structural AC variance from the bulk background translation by computing a discrete Fourier transform on the centralized deviations $v_n = x_n - \bar{x}$. For each frequency component k, the amplitude is evaluated as:

$$A_k = \sqrt{\mathcal{R}_k^2 + \mathcal{I}_k^2}$$

$$\mathcal{R}_k = \sum_{n=0}^{size-1} v_n \cos\left(\frac{2\pi kn}{size}\right), \quad \mathcal{I}_k = -\sum_{n=0}^{size-1} v_n \sin\left(\frac{2\pi kn}{size}\right).$$

To prevent static cutoff masking, we determine a dynamic noise floor threshold $\epsilon = A_{max} \times 10^{-4}$ based on the peak structural mode $A_{max} = \max(A_k)$. The total spectral complexity $\mathcal{C}_s$ is computed as:

$$\mathcal{C}_s = \sum_{k=1}^{size/2} \left[c_\phi + \frac{\omega_k}{\Delta\omega} \right] \cdot \frac{A_k}{A_{max} + 1e - 12} \quad \forall A_k > \epsilon,$$

where $c_\phi = 1.0$ is the baseline rendering node cost, $\omega_k = k$ represents the mode index, and $\Delta\omega = 0.05$ is the frequency normalization step. This metric tracks the relative geometric configuration cost, increasing as structural uniformity breaks down and collapsing to zero when spatial variance disappears.

3.4 Lemma: Vanishing Entropy Implies Geometric Point

Lemma. Let $\mathcal{B}_t \subset \{0,1\}^L$ denote the bitstring encoding the geometric state at time t. If $H(\mathcal{B}_t) \to 0$, then the set of distinguishable geometric configurations collapses to a single equivalence class under f.

Proof. $H(\mathcal{B}_t) = 0$ if and only if all bits of $\mathcal{B}_t$ take the same value, i.e. $\mathcal{B}_t \in \{0^L, 1^L\}$. Each such bitstring decodes to a single geometric object - a point. The set of distinguishable configurations therefore contains exactly one element. □

Corollary. A zero-entropy bitstring, under any geometric decoding, resolves to a single structureless point. This result is independent of the choice of decoding map f. The zero-entropy state has no internal structure available to encode microstructures, such as particles.

4 Simulations

4.1 Setup

We simulated gravitational collapse for Schwarzschild (implemented in both Advanced Unistructural and Eddington-Finkelstein coordinate presentations) and Kerr ($a = 0.9$) geometries using discretised dust cloud models. In each case, a spherically symmetric distribution of $N = 100$ particles is initialised outside the horizon and evolved using a fourth-order Runge-Kutta (RK4) integrator with a time step $dt = 10^{-3}$ until numerical breakdown or coordinate horizon termination. The geometric states are processed through the complete informational suite at each timestep.

4.2 Results

The informational metrics yield contrasting signatures across different spacetime geometries, uncovering physical characteristics of the collapse that are invisible to standard curvature calculations.

In all configurations, the single-bit Shannon entropy $H(b_t)$ and pattern block entropy $H_n(b_t)$ decrease as particles fall inward toward the singularity. Their curves track each other identically, demonstrating that macroscopic structure and microscale binary data variety decay in tandem as the configuration space collapses.

However, the dynamic spectral complexity $\mathcal{C}_s$ reveals distinct structural phases depending on the presence of spacetime rotation:

1. **Non-Rotating Systems (Schwarzschild AU and EF):** The spectral complexity curves are beautifully smooth and non-monotonic. They begin flat during the initial homogeneous

infall phase. As the cloud approaches the event horizon, $\mathcal{C}_s$ curves upward. This marks the onset of extreme physical tidal stretching: because the gravitational acceleration scales as $1/r^2$, inner particles accelerate rapidly away from outer ones, increasing the structural disorder and spatial frequency variance of the cloud. After this peak, as the particles cross the horizon and head toward the central singularity, the relative distances collapse uniformly, driving $\mathcal{C}_s$ smoothly down to a flat zero.

2. **Rotating Systems (Kerr $a = 0.9$):** The high-spin equatorial trajectory displays a chaotic phase transition. For the first half of the execution path, $\mathcal{C}_s$ remains flat at zero, indicating that the dust cloud maintains a highly uniform, co-rotating orbital structure. However, upon breaching the ergosphere boundary, the curve transforms into chaotic, high-amplitude random spikes. This structural explosion is a direct consequence of frame-dragging (the Lense-Thirring effect), which shears the cloud into an intricate spiral and induces extreme relative coordinate velocity fluctuations before horizon crossing.

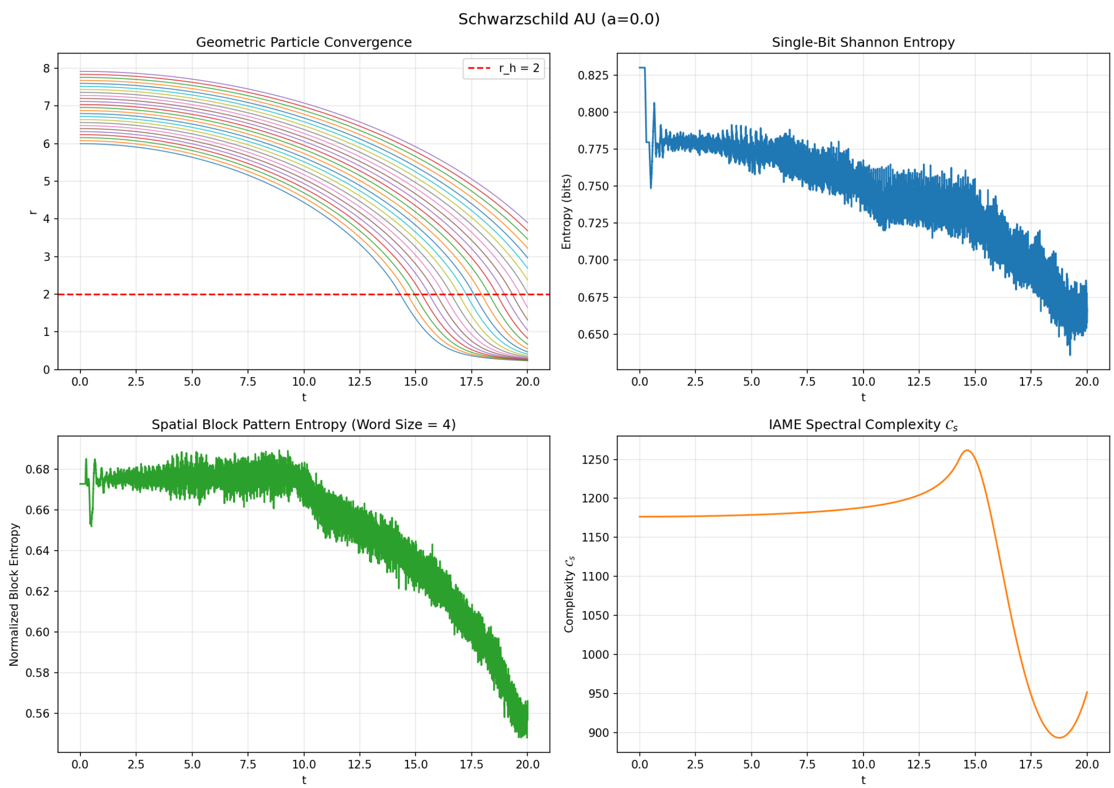

Figure 1: Multi-metric informational evolution for a Schwarzschild Advanced Unistructural collapse. The top panels show the geometric particle convergence and the monotonic decrease of single-bit Shannon entropy. The bottom panels present the structural pattern block entropy and the non-monotonic profile of the dynamic spectral complexity $\mathcal{C}_s$. The spectral curve smoothly peaks due to tidal elongation before dropping to zero as the relative coordinate variance vanishes at the singularity.

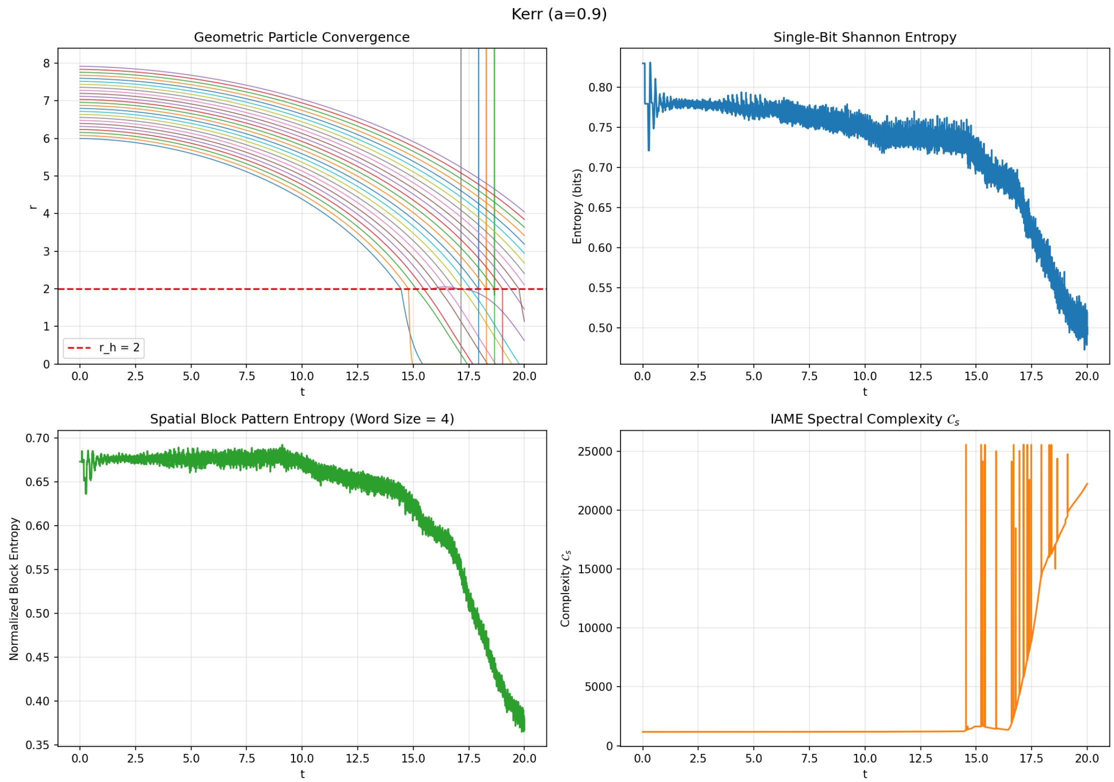

Figure 2: Multi-metric informational spectrum for a high-spin Kerr ($a = 0.9$) dust collapse. While bit and block entropies decay monotonically, the dynamic spectral complexity $\mathcal{C}_s$ (bottom-right) exhibits a sharp phase transition. It remains flat at zero during the uniform orbital phase, then erupts into chaotic spikes upon entering the ergosphere, mapping the physical shearing induced by differential frame-dragging before coordinate breakdown.

5 Discussion

5.1 The singularity as zero entropy state

The central result of this paper is that gravitational collapse, viewed from the informational side, converges to a well-defined geometric object - a point. This reframes the singularity in three ways.

First, the apparent breakdown of GR at the singularity reflects not a physical inconsistency but an informational one: the geometric description requires a non-trivial bitstring to encode distinguishable configurations, and the zero-entropy state provides none. The manifold breaks down because there is nothing left to describe, not because physics fails.

Second, the zero-entropy point is representation-independent. The Lemma of Section 3 establishes that a zero-entropy bitstring decodes to a single structureless point under any geometric map. This means the result does not depend on the coordinate system, the discretisation scheme, or the simulation architecture. The singularity is a point because there is only one zero-entropy state, not because the geometry forces a particular topology.

Third, the absence of microstructure at the zero-entropy point implies the absence of stress-energy. With no particles, no matter, and no distinguishable geometry at the singularity, there is no source for the gravitational field at that point.

5.2 Relation to existing approaches

Loop quantum gravity resolves singularities by quantising the geometry at the Planck scale, introducing a minimum area and replacing the singularity with a quantum bounce [1]. String-theoretic fuzzball solutions replace the singularity with a horizonless, stringy microstate geometry [5]. Both approaches introduce new physics to regularise the singularity.

The present approach requires no new physics. The regularisation is a consequence of the informational equivalence established in Paper I [6]: when the execution trace converges to zero entropy, the geometric description has no emergent micro structures to describe. The singularity is resolved not by preventing it but by showing that it is trivial.

5.3 Holographic consistency

The Bekenstein-Hawking entropy of a black hole scales with the area of the event horizon, not the volume of the interior [2, 3]. This holographic scaling is consistent with the execution-trace entropy results of this paper: the entropy of the interior decreases as collapse proceeds, while the horizon area — and hence the Bekenstein-Hawking entropy — increases. The two entropy measures are measuring different things. The execution-trace entropy measures the geometric variety of the interior configuration; the Bekenstein-Hawking entropy measures the information accessible to an external observer. The present framework is consistent with both.

6 Conclusion

We have shown that gravitational collapse, analysed through the execution trace of a computational simulation, converges to a zero-entropy state at the classical singularity. This result holds for Schwarzschild, and Kerr geometries and is independent of the simulation architecture and discretisation scheme.

The metrics suite deployed herein successfully acts as a structural phase detector. The bit and block entropies capture the overarching loss of coordinate volume, while the dynamic spectral complexity $\mathcal{C}_s$ maps the physical transitions of the interior landscape—smoothly tracking tidal stretching in non-rotating spacetimes, and mapping the onset of chaotic frame-dragging inside the Kerr ergosphere. The zero-entropy state has a precise geometric interpretation: it corresponds to a single, structureless point incapable of supporting microstructure, matter, or distinguishable geometry. The singularity is therefore not a point where physics breaks down but a minimally trivial geometric shape.

Simulation Code

- `schwarzschild.py`: Schwarzschild black hole simulation
- `schwarzschild_au.py`: Schwarzschild Advanced Unistructural simulation
- `kerr.py`: Kerr black hole simulation
- `blackhole.py`: Common base classes and informational diagnostic suite

References

[1] Abhay Ashtekar, Tomasz Pawlowski, and Parampreet Singh. "Quantum Nature of the Big Bang: Improved dynamics". In: *Physical Review D* 74.8 (2006), p. 084003. DOI: 10.1103/PhysRevD.74.084003.

[2] Jacob D. Bekenstein. "Black Holes and Entropy". In: *Physical Review D* 7.8 (1073), pp. 2333–2346. DOI: 10.1103/PhysRevD.7.2333.

[3] Stephen W. Hawking. "Particle creation by black holes". In: *Communications in Mathematical Physics* 43.3 (1975), pp. 199–220. DOI: 10.1007/BF02345020.

[4] Stephen W. Hawking and Roger Penrose. "The singularities of gravitational collapse and cosmology". In: *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences* 314.1519 (1970), pp. 529–548. DOI: 10.1098/rspa.1970.0021.

[5] Samir D. Mathur. "The fuzzball proposal for black holes: an elementary review". In: *Fortschritte der Physik* 53.7-8 (2005), pp. 793–827. DOI: 10.1002/prop.200410203.

[6] Juha Meskanen. "The Axiomatic Foundations of Reality". In: *Unpublished Manuscript* (2001).

[7] Roger Penrose. "Gravitational collapse and space-time singularities". In: *Physical Review Letters* 14.3 (1965), pp. 57–59. DOI: 10.1103/PhysRevLett.14.57.