


An IR complete framework for Quantum Gravity in D-dimensions

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Abstract

We compile a high-level but specific overview of a quantum-gravity framework in which spacetime undergoes localized, entropy-triggered dimensional reduction $D \rightarrow D - 2$. The transition occurs on internal surfaces (“ledgers” \mathcal{L}) where a *dimensionless* curvature invariant \mathcal{I} reaches a universal threshold $\mathcal{I}_{\text{crit}} = 12/\mathcal{T} = 48 \ln 2$. In the Schwarzschild family, $\mathcal{I} = r^4 K$ with $K = R_{ABCD} R^{ABCD}$ places the ledger at $r_{\mathcal{L}} = \sqrt{\mathcal{T}} R_S$. Across a snap, Null-Pair Removal (NPR) deletes a null two-plane, while the Law of Transdimensional Thermodynamics (TDT) balances payload against capacity: $dS_{\mathcal{L}} = dS_{\text{info}}$, implying an area-per-bit quantum $\Delta\mathcal{A} = 4 \ln 2 \ell_P^2$ consistent with black-hole thermodynamics [1, 2]. Each ledger tile stores a minimal reversible record (“Infinity Bits”): $\{\text{br}, X, Y, Z\}$, built from boost-invariant combinations of orientation, shear alignment, and normal-bundle twist [3, 4]. Between snaps, \mathcal{L} supports a worldvolume EFT; coarse-graining yields a master equation and a master path integral that sum over snap insertions. Phenomenology includes inner-boundary conditions for perturbations (gravitational-wave echoes) [5, 6, 7], Hawking-flux bookkeeping [2], and the sequestering of a would-be radion fifth force in 4D. Dark matter is attributed to stabilized remnant black holes (capacity protection and mode-gap kinematics), while the coarse-grained ledger sector provides a nearly constant dark-energy-like component with $w \simeq -1$. This note fixes definitions, equations, and claims for priority; detailed derivations appear in modular follow-ups.

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Introduction

Black-hole thermodynamics [1, 2] and the focusing of null congruences via the Raychaudhuri equation [8, 9] suggest that information and geometry are tightly coupled at horizons and caustics. We posit a concrete, IR-complete mechanism: when a *dimensionless* curvature invariant \mathcal{I} reaches a universal threshold $\mathcal{I}_{\text{crit}}$, spacetime locally loses two dimensions across an internal surface \mathcal{L} . The deleted directions are null, and the surviving $(D - 2)$ -surface stores a minimal reversible record of the update. The local geometry on \mathcal{L} is characterized by the induced metric h_{ab} , null expansions θ_{\pm} , shears $\sigma_{ab}^{(\pm)}$, the Hájíček one-form ω_a , and its curvature $\mathcal{F}_{ab} = \nabla_a \omega_b - \nabla_b \omega_a$ [3, 4]. This manifest formalizes the framework that builds upon and supersedes the foundational concepts first explored in an earlier thesis [10].

The global bookkeeping is governed by the Law of Transdimensional Thermodynamics (TDT), which links *irreversible* payload to a geometric capacity increase of the ledger area. This yields a fixed area-per-bit $\Delta\mathcal{A} = 4 \ln 2 \ell_{\text{P}}^2$, dovetailing with the Bekenstein–Hawking area law [1, 2]. Between snaps, \mathcal{L} supports an intrinsic EFT and imposes inner boundary conditions on perturbations, producing ringdown echoes in black-hole mergers [5, 6, 7]. A master equation (coarse-grained) and a master path integral (microscopic) summarize the dynamics, while a focused “junction” view keeps Raychaudhuri classical between snaps and enforces NPR+TDT only at threshold crossings. Cosmologically, the coarse-grained ledger sector behaves as a smooth component with $w \simeq -1$, and evaporation halts in a Planckish remnant window—natural cold dark-matter candidates.

A key result of this framework is the derivation of a new, universal transdimensional constant of nature, $\mathcal{T} = 1/(4 \ln 2)$. This dimensionless constant is not a free parameter, but is fixed by the information-theoretic structure of a single “snap” event. We show that \mathcal{T} acts as a fundamental coupling constant that connects geometry, thermodynamics, and quantum information, setting the scale for the ledger’s location, its information capacity, and the very trigger for dimensional collapse.

We now state the concrete pieces used throughout the framework. ¹

1 Numerical anchors, invariant, placement

1.1 Dimensionless trigger and scaling

Define the invariant

$$\mathcal{I} \equiv L^4 K, \quad K \equiv R_{ABCD} R^{ABCD},$$

with L set by the symmetry family (e.g. $L = r$ for spherically symmetric spacetimes). In $D = 4$ Schwarzschild,

$$K = \frac{48M^2}{r^6}, \quad \mathcal{I}(r) = r^4 K = 12 \left(\frac{R_{\text{S}}}{r} \right)^2.$$

The choice of a *dimensionless* scalar ensures gauge/coordinate independence of the snap condition.

¹For notation and conventions see Appendix A

1.2 Threshold and constants

The constant \mathcal{T} is fixed by the theory's information-payload structure (a 1-in-4 bit ratio, normalized by $\ln 2$ for thermodynamic consistency). The key numerical anchors are:

$$\mathcal{T} = \frac{1}{4 \ln 2} \approx 0.36067376, \quad \sqrt{\mathcal{T}} \approx 0.36067376, \quad \mathcal{I}_{\text{crit}} = \frac{12}{\mathcal{T}} = 48 \ln 2 \approx 33.27106467.$$

These set the universal level set $\mathcal{I} = \mathcal{I}_{\text{crit}}$ for ledger placement.

1.3 Ledger placement: spherical and axisymmetric

For Schwarzschild,

$$\mathcal{I}|_{\mathcal{L}} = \mathcal{I}_{\text{crit}} \implies r_{\mathcal{L}} = \sqrt{\mathcal{T}} R_{\text{S}}.$$

In axisymmetry (Kerr/Kerr–Newman), choose $L^4 K(r, \theta)$ with the standard Boyer–Lindquist curvature invariants; $r_{\mathcal{L}}(\theta)$ then solves

$$\mathcal{I}(r, \theta) = \mathcal{I}_{\text{crit}}, \quad A(\mathcal{L}) = \int_0^{2\pi} \int_0^\pi \sqrt{\det h_{ab}(r_{\mathcal{L}}(\theta), \theta)} \, d\theta \, d\phi.$$

The ratio $S_{\mathcal{L}}/S_{\text{BH}}$ remains \mathcal{T} for stationary families under these conventions.

2 Dimensional Collapse Theory (DCT): trigger and ladder

2.1 Snap definition

A localized transition $D \rightarrow d$ occurs across surfaces \mathcal{L} where

$$\mathcal{I}|_{\mathcal{L}} = \mathcal{I}_{\text{crit}},$$

and the removed directions are null. The d -dimensional \mathcal{L} is the *ledger* carrying the minimal reversible record.

2.2 Ladder and frozen ground

Iterating snaps in even D yields a ladder $\cdots \rightarrow 8 \rightarrow 6 \rightarrow 4 \rightarrow 2$. In $D = 2$ (two-dimensional ground), there are no local bulk propagating modes; evolution is topological/edge-like.

2.3 Why dimensionless and geometric

Because \mathcal{I} is a scalar constructed from K with a fixed length scale L , the trigger is independent of coordinates and local boosts; it is also insensitive to rescalings of affine parameters.

3 Null–Pair Removal (NPR): what a snap deletes

Having established the geometric condition for a snap, we must now define precisely what spacetime structures are removed in the process. This is the role of Null-Pair Removal (NPR).

3.1 Projector algebra and gauge

Pick null directors n_{\pm}^A with $n_{\pm} \cdot n_{\pm} = 0$, $n_+ \cdot n_- = 1$. Define

$$P^A_B = \delta^A_B - n_+^A n_B^- - n_-^A n_B^+.$$

Then $P^A_C P^C_B = P^A_B$ (idempotent), $P^A_B n_{\pm}^B = 0$, and $\text{Tr } P = d$. Under $SO(1, 1)$ boosts $n_{\pm} \rightarrow e^{\pm\lambda} n_{\pm}$, the projector is invariant.

3.2 Action on fields

For a vector V^A , write $V^A = V_{\parallel}^A + V_{\perp}^A$ with $V_{\parallel}^A = \alpha n_+^A + \beta n_-^A$, $V_{\perp}^A = P^A_B V^B$. NPR deletes V_{\parallel} . For tensors, apply P on each index. The induced metric on the ledger, h_{ab} , is the projection of the ambient metric g_{AB} using this operator.

3.3 Transport rule

Transport across \mathcal{L} is permitted only during writes (snaps). Between snaps, \mathcal{L} acts as an inner boundary determined by a kernel (Sec. 8).

4 Law of Transdimensional Thermodynamics (TDT): capacity vs payload

While NPR describes the geometric deletion, the Laws of Transdimensional Thermodynamics (TDT) govern the information and entropy bookkeeping of the process, ensuring consistency with established horizon thermodynamics.

4.1 Capacity law and one-bit quantum

Ledger capacity obeys

$$S_{\mathcal{L}} = \frac{A(\mathcal{L})}{4\ell_{\text{P}}^2}, \quad \Delta \mathcal{A}_{\text{one bit}} = 4 \ln 2 \ell_{\text{P}}^2, \quad \Delta S_{\mathcal{L}} = \ln 2.$$

The one-bit area is universal and matches the Bekenstein–Hawking logic [1, 2].

4.2 Payload–capacity balance and current form

At a snap,

$$dS_{\mathcal{L}} = dS_{\text{info}}.$$

Equivalently, in a local covariant form with a surface entropy current s^a intrinsic to \mathcal{L} ,

$$\nabla_a s^a = \Phi_S,$$

where Φ_S is a scalar source localized on the snap hypersurface (delta-supported); between snaps $\nabla_a s^a = 0$.

4.3 Consistency checks

(i) *Additivity*: disjoint snap patches add capacities and payloads linearly. (ii) *Locality*: Φ_S is delta-supported on the snap hypersurface. (iii) *Second law*: irreversible bits increase S_{ledger} monotonically.

5 Infinity Bits: minimal reversible record per tile

For the dimensional reduction to be fundamentally reversible (up to gauge freedom), the ledger must store a minimal set of geometric metadata. We define this record as the four boost-invariant Infinity Bits.

5.1 Definition and invariances

Per tile, store

$$\{\text{br}, X, Y, Z\}.$$

br is the payload/branch bit. Geometric bits:

$$X = \text{sgn}(\varepsilon_{ABCD} e_1^A e_2^B n_+^C n_-^D), \quad Y = \text{sgn}(\sigma_{ab}^{(+)} \sigma^{(-)ab}), \quad Z = \text{sgn}(\epsilon^{ab} \mathcal{F}_{ab}),$$

with $\mathcal{F}_{ab} = \nabla_a \omega_b - \nabla_b \omega_a$. All are invariant under $SO(1,1)$ boosts.

5.2 Degeneracies and tie-breakers

On measure-zero sets (e.g. $\sigma_{ab}^{(+)} \sigma^{(-)ab} = 0$ or $\epsilon^{ab} \mathcal{F}_{ab} = 0$), adopt fixed local conventions (lexicographic frame choice or infinitesimal regulator) to maintain reversibility.

5.3 Sufficiency for reversibility

Given $\{\text{br}, X, Y, Z\}$ and smoothness, NPR can be inverted up to diffeomorphisms and boost gauge to re-embed the patch.

6 Focused Raychaudhuri & junction picture

With the rules of the snap established, we now place them within the context of classical spacetime dynamics, showing how the ledger acts as a regulated junction that replaces the classical singularity predicted by the Raychaudhuri equation.

6.1 Classical focusing between snaps

Let k^a be a null generator, $\theta = \nabla_a k^a$, shear σ_{ab} , twist ω_{ab} . Then

$$\frac{d\theta}{d\lambda} = -\frac{1}{2}\theta^2 - \sigma_{ab}\sigma^{ab} + \omega_{ab}\omega^{ab} - R_{ab}k^a k^b.$$

Under standard energy conditions and vanishing twist, focusing drives congruences toward caustics [8, 9].

6.2 Junction at the snap

The snap is triggered by $\mathcal{I} = \mathcal{I}_{\text{crit}}$, not by $\theta \rightarrow -\infty$. Across \mathcal{L} :

- Apply NPR ($P^A{}_B$) on fields; keep the induced h_{ab} continuous.
- Update capacity via TDT; payload br fixed by the branch predicate.
- Impose inner boundary conditions for perturbations (Robin-type) set by a kernel on \mathcal{L} .

This is analogous in spirit to null-shell junctions [11] but with NPR/TDT structure and no sustained NEC violation.

7 Proper vs. “apparent” entropy (ledger vs. horizon)

The placement and thermodynamics of the ledger create a direct mapping between its own proper entropy and the Bekenstein-Hawking entropy of the encompassing event horizon, which we now make explicit.

7.1 Definitions and mapping

$$S_{\text{proper}} = S_{\mathcal{L}} = \frac{A(\mathcal{L})}{4\ell_{\text{P}}^2}, \quad S_{\text{apparent}} = S_{\text{BH}} = \frac{A_{\text{H}}}{4\ell_{\text{P}}^2}.$$

For Schwarzschild,

$$S_{\mathcal{L}} = \mathcal{T} S_{\text{BH}}, \quad r_{\mathcal{L}} = \sqrt{\mathcal{T}} R_{\text{S}}.$$

7.2 Axisymmetric computation

Let $\mathcal{L} : r = r_{\mathcal{L}}(\theta)$ in Boyer–Lindquist-like coordinates. With induced h_{ab} on the angular 2-surface,

$$A(\mathcal{L}) = \int \sqrt{\det h_{ab}(r_{\mathcal{L}}(\theta), \theta)} d\theta d\phi.$$

The ratio $A(\mathcal{L})/A_{\text{H}} = \mathcal{T}$ fixes normalization conventions across families.

8 IR QG EFT: master equation and path integral (arbitrary D)

To describe the full quantum dynamics, we synthesize these principles into a complete effective field theory, formulating the ledger’s behavior as boundary conditions within a master equation and, more fundamentally, as localized insertions in a master path integral.

8.1 Ledger EFT (microscopic, between snaps)

$$\begin{aligned} {}^{(d)}S_{\text{ledger}}[h, \phi] = \int_{\mathcal{L}} d^d\xi \sqrt{|h|} \Big[-\tfrac{1}{2} Z_D({}^{(d)}R, K_{ab}K^{ab}, K^2, \dots) h^{ab}(\nabla_a\phi)(\nabla_b\phi) \\ -\tfrac{1}{2} m_D^2 \phi^2 + \beta_D \phi \psi|_{\mathcal{L}} + \dots \Big]. \end{aligned}$$

Here $d = D - 2$, h_{ab} is the induced metric on \mathcal{L} , ∇ the intrinsic covariant derivative, and K_{ab} the extrinsic curvature of \mathcal{L} . The mixing term $\beta_D \phi \psi|_{\mathcal{L}}$ couples a representative bulk perturbation ψ pulled back to \mathcal{L} . In late-time 4D, $m_4 \gtrsim M_{\text{P}}$ sequesters ϕ (no long-range fifth force).

8.2 Inner boundary kernel and Robin data (effective)

$$(\partial_n \psi)|_{\mathcal{L}} = \mathbf{B} \psi|_{\mathcal{L}}, \quad \mathbf{R}(\omega) = \frac{\mathbf{B} - i\omega}{\mathbf{B} + i\omega} e^{2i\varphi}.$$

At quadratic order, integrating out ϕ in ${}^{(d)}\mathcal{S}_{\text{led}}$ induces the effective boundary action

$${}^{(d)}S_{\text{BC}}[\psi] = \frac{1}{2} \int_{\mathcal{L}} d^d \xi \sqrt{|h|} \psi \mathbf{B} \psi.$$

8.3 Master equation (coarse-grained)

$$\partial_t \rho = -i [H_{\text{bulk}} + H_{\text{led}} + H_{\text{BC}}, \rho] + \sum_i \left(\mathcal{J}_i[\rho] - \rho \right) \delta(\Sigma_i),$$

where \mathcal{J}_i are the CPTP snap instruments supported on the snap hypersurfaces Σ_i . The term $(\mathcal{J}_i - \mathbb{I})[\rho]$ correctly represents the instantaneous update of the state at the snap.

8.4 Master path integral (microscopic, with episodic snaps)

$$\mathcal{Z} = \int \mathcal{D}g \mathcal{D}\Psi \mathcal{D}\psi \mathcal{D}\phi \exp \left\{ i \left[{}^{(D)}\mathcal{S}_{\text{EH}}[g] + {}^{(D)}\mathcal{S}_{\text{matter}}[g, \Psi] + {}^{(d)}\mathcal{S}_{\text{BC}}[\psi] \right] \right\} \\ \prod_i \exp \left\{ i {}^{(d)}\mathcal{S}_{\text{snap}}^{(i)}[g; P, \mathcal{I} = \mathcal{I}_{\text{crit}}] \right\}.$$

If no hypersurface satisfies $\mathcal{I} = \mathcal{I}_{\text{crit}}$, the product is empty and one recovers standard GR+QFT.

9 Phenomenology: gravitons, echoes, Hawking bookkeeping, radion

The formal structure of the EFT leads directly to a set of concrete, falsifiable predictions. We now outline the primary phenomenological signatures of the framework.

9.1 Graviton sector and energy flux

Linearized h_{AB} exists for $D \geq 4$. In 4D, two TT polarizations; wave-zone flux from Isaacson stress tensor. Inner boundary at \mathcal{L} modifies ingoing/outgoing mode mixing.

9.2 Echo cavity and spacing

With tortoise coordinate r_* , define the travel time

$$T(r) = \int^r \frac{dr'}{f(r')}, \quad \text{family-dependent } f,$$

so the cavity spacing is

$$\Delta t \approx 2 [T(r_{\text{barrier}}) - T(r_{\mathcal{L}})], \quad \Delta f = \frac{1}{\Delta t},$$

with amplitude/phase set by $\mathbf{R}(\omega), \varphi$ [5, 6, 7].

9.3 Hawking bookkeeping

Leading flux remains Hawking-like [2]; snaps correlate the outgoing state episodically, preserving global unitarity while avoiding information loss. No late-time explosive bursts if remnants persist (Sec. 9).

9.4 Radion and fifth force

On the 2+1-dimensional ledger in 4D, the radion ϕ is heavy/constraint-like (range $\ell_{\text{rad}} \lesssim \ell_{\text{P}}$); boundary couplings are contact-like between snaps. Hence no detectable long-range fifth force in 4D.

10 Dark sector: stabilized remnants (DM) & smooth component (DE)

Beyond local tests, the theory's thermodynamic principles have profound consequences on cosmological scales, offering a unified physical origin for the entire dark sector.

10.1 Capacity-protection floor

In Planck units,

$$S_{\text{rem}}(M) = \frac{A(\mathcal{L})}{4\ell_{\text{P}}^2} = \mathcal{T} S_{\text{BH}}(M) = 4\pi\mathcal{T} M^2, \quad \Delta\mathcal{A} = 4 \ln 2 \ell_{\text{P}}^2,$$

so with N_{irr} irreversible bits already written,

$$M_{\text{rem}}(N_{\text{irr}}) \geq \frac{\ln 2}{\sqrt{\pi}} \sqrt{N_{\text{irr}}} M_{\text{P}} \gtrsim 0.3911 \sqrt{N_{\text{irr}}} M_{\text{P}} \quad (N_{\text{irr}} \geq 1).$$

10.2 Mode-gap bound

With $\Delta t(M)$ from the cavity,

$$k_{\text{B}} T_{\text{H}} \lesssim \hbar \pi / \Delta t(M) \Rightarrow M_{\text{rem}} \gtrsim C_{\text{kin}}(\mathcal{T}, \mathcal{R}, \varphi) M_{\text{P}}.$$

A Planckish remnant window follows from two independent mechanisms.

10.3 DE as coarse-grained ledger sector

$$w_{\mathcal{L}} \equiv \frac{p_{\mathcal{L}}}{\rho_{\mathcal{L}}} \approx -1 + \delta w(z), \quad |\delta w| \ll 1,$$

originating from episodic updates. Zeroth order $w_{\mathcal{L}} \simeq -1$. Dedicated fits (SNe+BAO+CMB) will constrain $\delta w(z)$.

11 Falsifiability & near-term tests

A viable physical theory must be falsifiable. We conclude by compiling a concise list of clear, near-term observational tests that could either support or rule out this framework.

- **Echo comb:** non-detection at predicted $\Delta f = 1/\Delta t$ across high-SNR mergers disfavors reflective \mathcal{L} at $r_{\mathcal{L}}$.
- **Ledger radius:** independent inference of $r_{\mathcal{L}}/R_S$ inconsistent with $\sqrt{\mathcal{T}}$.
- **Cosmology:** joint SNe+BAO+CMB constraints exclude all $\delta w(z)$ compatible with episodic updates.
- **Stars:** a static-star configuration saturating $\mathcal{I} \geq \mathcal{I}_{\text{crit}}$ under standard energy conditions.
- **Remnants:** absence of terminal Hawking bursts and compatibility with microlensing/structure constraints for Planckish remnants.

12 Priority claims (compact)

- **C1** The universal transdimensional constant, $\mathcal{T} = 1/(4 \ln 2)$, from a fundamental information-capacity ratio.
- **C2** $\mathcal{I} = \mathcal{I}_{\text{crit}}$ with $\mathcal{T} = 1/(4 \ln 2)$, $\mathcal{I}_{\text{crit}} = 48 \ln 2$.
- **C3** $r_{\mathcal{L}} = \sqrt{\mathcal{T}} R_S$; axisym: $\mathcal{I}(r, \theta) = \mathcal{I}_{\text{crit}}$.
- **C4** $dS_{\mathcal{L}} = dS_{\text{info}}$; one bit $\Rightarrow \Delta \mathcal{A} = 4 \ln 2 \ell_p^2$.
- **C5** Infinity Bits $\{\text{br}, X, Y, Z\}$ (boost-invariant geometry bits).
- **C6** Focused junction: classical Raychaudhuri between snaps; NPR+TDT at thresholds.
- **C7** $S_{\mathcal{L}} = \mathcal{T} S_{\text{BH}}$ for stationary families.
- **C8** Master equation with snap superoperators; master path integral summing snaps.
- **C9** Echo spacing rule $\Delta t \approx 2[T(r_{\text{barrier}}) - T(r_{\mathcal{L}})]$; radion sequestering (no 4D fifth force).
- **C10** Dark sector: stabilized Planckish remnants (DM) and a smooth $w_{\text{led}} \simeq -1$ component (DE).

13 Summary and Outlook

We proposed a concrete, testable program for quantum gravity in which localized, thresholded dimensional reduction implements information-preserving updates on \mathcal{L} . The key inputs are (i) a dimensionless trigger $\mathcal{I} = \mathcal{I}_{\text{crit}}$ fixing ledger placement, (ii) NPR as the minimal geometric deletion with a reversible metadata set (Infinity Bits), and (iii) TDT linking payload to capacity with a universal area-per-bit. Between snaps, \mathcal{L} hosts an intrinsic EFT and supplies boundary

conditions for perturbations. Phenomenology spans gravitational-wave echoes, Hawking-flux bookkeeping, non-observation of a 4D fifth force (radion sequestering), stabilized Planckish remnants as DM, and a smooth $w \simeq -1$ sector as DE. Immediate priorities include: deriving axisymmetric placement and echo transfer functions, formalizing the snap superoperators in the master equation, quantifying $\delta w(z)$ in cosmology, and mapping remnant abundance against observational bounds. The claims above are concise enough to establish priority while leaving room for detailed papers.

A Notation and Conventions

Units and signature. We use natural units $c = \hbar = k_B = 1$. Planck length ℓ_P is kept explicit. Unless stated, G is explicit in geometric identities and set to 1 in back-of-the-envelope estimates. Metric signature is $(-, +, +, +)$ in 4D, and $(-, +, \dots, +)$ in D dimensions. Curvature conventions:

$$R^a{}_{bcd} = \partial_c \Gamma^a_{bd} - \partial_d \Gamma^a_{bc} + \Gamma^a_{ce} \Gamma^e_{bd} - \Gamma^a_{de} \Gamma^e_{bc}, \quad R_{ab} = R^c{}_{acb}.$$

Dimensional tags. We mark the dimension of geometric objects with *left* superscripts in parentheses:

$$^{(D)}G_{AB}, \quad ^{(D)}\nabla, \quad ^{(D)}\square, \quad ^{(d)}R_{ab}, \quad ^{(2)}\epsilon_{\perp ab}.$$

Here D is the ambient spacetime dimension and $d := D - 2$ is the ledger dimension. Indices A, B, \dots are ambient; a, b, \dots live on the ledger \mathcal{L} ; the normal two-plane is denoted by $^{(2)}(\cdot)$. Right superscripts are reserved for powers, perturbative orders, or labels unrelated to dimension.

DCT triad and invariants. We use the calligraphic triad $(\mathcal{L}, \mathcal{I}, \mathcal{T})$:

$$\mathcal{L} \text{ (ledger surface)}, \quad \mathcal{I}(r) \equiv r^4 K(r), \quad K = R_{ABCD} R^{ABCD}, \quad \mathcal{T} = \frac{1}{4 \ln 2}.$$

The universal snap threshold is

$$\mathcal{I}_{\text{crit}} = 48 \ln 2 = \frac{12}{\mathcal{T}},$$

fixing, for Schwarzschild, the ledger placement $r_{\mathcal{L}} = \sqrt{\mathcal{T}} R_S$ (axisymmetric generalizations use the canonical slice).

Thermodynamics and information. All entropies are in *nats*. Ledger entropy $S_{\mathcal{L}} = A/(4\ell_P^2)$. At a snap, the capacity–payload equality holds,

$$\delta S_{\mathcal{L}} = \delta S_{\text{info}},$$

and one *irreversible payload bit* costs

$$\Delta \mathcal{A}_{\text{one bit}} = 4 \ln 2 \ell_P^2.$$

Reversible geometric metadata (X, Y, Z) (the *Infinity Bits*) do not change von Neumann entropy. We summarize this ethos as: *no record without area*.

Mechanism and dynamics. Snaps are *Null–Pair Removal* (NPR) events: if n_{\pm}^A span the deleted null 2-plane with $n_+ \cdot n_- = 1$,

$$P^A{}_B = \delta^A{}_B - n_+^A n_B^- - n_-^A n_B^+$$

projects data onto the ledger surface \mathcal{L} ; local $SO(1, 1)$ boosts in the deleted plane are gauge. Transport across \mathcal{L} is permitted only during snaps. Between snaps, the ledger imposes a *real*

Robin boundary (lossless, $|R| = 1$), so evolution is unitary. At a snap, the open system updates via a localized CP–TP instrument and writes the irreversible payload bit to \mathcal{L} .

Bits vs. nats. We write information in nats; 1 bit = $\ln 2$ nats. When convenient, we annotate payload in bits and convert via $\ln 2$.

Default dimension. Unless a left superscript is shown, quantities are $D = 4$. We tag $^{(D)}(\cdot)$, $^{(d)}(\cdot)$, or $^{(2)}(\cdot)$ only when comparing across dimensions or when a quantity lives intrinsically on \mathcal{L} or on the normal two-plane.

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