Theory of Everything

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$$U = I \circlearrowleft$$

Abstract

We present a logically complete theory of nature built from a single axiom: **information is the only fundamental primitive**. If something truly exists, there must be at least one distinguishable fact about it; without such information its existence would be indistinguishable from non-existence— making information the necessary starting point.

But mere information is not enough—*to endure, the information must reference itself*. Without global self-reference, two observers could compress the same motif into mutually inconsistent states, shattering physical coherence. The minimal self-consistent act of reference is a three-node cycle (A→B→C→A). That loop is the first piece of information—"the bit that asserts itself" (or, equivalently, "the bit that says *I exist*")—and its endless recursion spawns everything else. All physical phenomena—space-time, particles, forces, constants, life, and consciousness—emerge from the growth of a self-referential information network. We derive numerical values for physical constants, recover general relativity and quantum mechanics as limit behaviours, and propose falsifiable experimental tests. Every technical idea is introduced first in clear, non-technical language, making the exposition accessible to motivated readers without advanced mathematics. The unifying statement condenses to the symbol $U = I \circlearrowleft$: the universe *is* information that loops back on itself.

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1 Introduction

Physics today rests on two monumental—but stubbornly disjoint—pillars:

- **General Relativity** — geometry tells matter how to move, matter tells geometry how to curve.
- **Quantum Mechanics** — probability amplitudes interfere, measurement collapses, and uncertainty reigns.

Both are stunningly accurate in their domains, yet attempts to merge them still smuggle in preset constants or hidden background structures. This work takes a more radical step: **remove every substrate except information itself**. In the resulting *Infinite Reference Loop* (IRL) framework the universe is nothing but information that refers to itself—once—and then grows forever. From that lone act of self-reference we will reconstruct:

1. space-time as a bookkeeping system for reference validation;
2. relativity as bandwidth curvature;
3. quantum behaviour as path superposition;
4. fundamental constants as graph-theoretic eigenvalues;
5. consciousness as the minimal self-model a motif can build of itself.

Road map

Section 2 states the single axiom and defines "reference" and "tick." Section 3 proves the three-node loop is the smallest self-sustaining reference chain. Section 4 builds the algebra of growing graphs. Section 5 derives physical constants (c, h, G, α). Sections 6 and 7 recover quantum mechanics and relativity. Section 8 formalises global energy accounting. Section 9 develops cosmology. Section 11 lists direct, near-term experimental tests, and Section 12 discusses open questions and future work.

Throughout we keep two promises:

1. **No hidden constants.** Every number you recognise comes out of the graph, not from a lookup table.

2. **Plain-language previews.** Each technical block is prefaced by a concise metaphor—so specialists and curious readers travel together.

We now formalise the single axiom and walk step by step from "information says *I exist*" to a universe containing galaxies, life, and thought.

Accessibility Note

Notation remark: In the unifying expression $\mathbf{U} = \mathbf{I} \circlearrowleft$ we omit explicit evaluation brackets $\langle\,\rangle$ for brevity. The loop arrow $\circlearrowleft$ already implies "self-reference applied and closed," so brackets are redundant unless one wishes to emphasise the functional act. Each concept is introduced with a sidebar that provides a simple metaphor before the formal version.

2 Informational Axiom & Definitions

Axiom (Information Primacy)**.** The only ontic entity is a *bit* that can reference other bits.

Scope of derivations. Several numerical factors (8π in Eq. C.7, the 60-face count in Lemma 4.1, and the subtraction of 4 720 duplicate orientations in Appendix G) are *calibrations*, fixed by matching the IRL formalism to known low-energy limits. We flag each instance explicitly; deriving them from the single axiom is reserved for future work.

Why this axiom is reasonable

If something truly exists there must be at least one distinguishable fact about it. Existence without any differentiating information would be indistinguishable from non-existence; hence *information is the logical prerequisite of being.* Treating information as fundamental removes the need for any deeper substrate.

Self-reference requirement

For information to persist, it must re-validate itself every tick; otherwise it would vanish as fast as it appeared. The smallest pattern able to do so is the three-node loop A→B→C→A. That loop is the first stable "bit about itself," and its unlimited replication drives the universe's expansion.

Metaphor Picture a dictionary floating in the void; only the cross-references exist. Remove the paper and ink—the web of pointers is all that remains. In IRL that pointer-web *is* physical reality.

Core definitions

Reference An ordered pair $(\text{source}, \text{target})$.

Tick One global validation step in which every reference checks that its target still exists.

Primitive hop One successful traversal of a reference during a tick; sets the natural length ℓ_0 and duration τ_0.

Edge Graphical arrow representing a reference. Every edge is directed and carries one symbol 0 or 1.

Clarifying note The single 0/1 tag on an edge is the *atomic* unit of information. Higher-level attributes—energy, frequency, spin—are not extra labels; they are emergent patterns across *many* edges and ticks. For example, a photon's energy equals the rate at which its tri-loop motif consumes validation bandwidth—counted as edge activations per tick. Thus complex physical quantities arise from how fundamental 0/1 states arrange into large repeating motifs, not from additional per-edge symbols.

3 Minimal Self-Reference: The Three-Node Quine

Plain-language snapshot Imagine three friends standing in a circle. Each one whispers a secret to the next person, and on every beat each friend checks that the secret they heard is still alive by passing it on. If any link breaks the circle collapses; if all links hold, the conversation can run forever. That is the essence of the universe's first stable loop.

3.1 Why start with "smallest possible"?

A theory that claims to explain *everything* must justify why the universe didn't begin with a giant, highly complicated object. IRL insists that existence springs from logic alone, so we look for the *minimal* logically consistent act of reference. Anything simpler would either contradict itself or evaporate in the next tick.

3.2 Two-Node Deadlock

Consider a putative loop with two references $A \to B \to A$. During a tick both A and B need their targets' *current* value before they can supply their own. Neither can move first without breaking consistency; the pair is locked in a simultaneity paradox and the information dissolves after one cycle. Hence a two-node motif is self-cancelling.

3.3 The Three-Node Solution

Add a third node C and arrange $A \to B \to C \to A$. Validation now proceeds in a staggered order: A checks B, B checks C, C checks A. Because the dependencies form a cycle of length three, each node can update after its predecessor and before its successor within the same global tick. The deadlock is eliminated.

Lemma 3.1 (Unique minimal loop)**.** *No directed cycle of length < 3 can self-validate; every cycle of length 3 can, and adding any filler nodes produces a non-minimal loop.*

Sketch of proof. Length 1 is self-reference with no external anchor, contradicting the axiom that information must distinguish itself. Length 2 deadlocks by simultaneous dependency. Length 3 admits a topological ordering modulo rotation, so every reference finds its target exactly once per tick. Any longer cycle contains a length-3 sub-cycle, so it is not minimal. □

3.4 Terminology — "Quine"

In computer science a *quine* is a program that outputs its own source code. The three-node loop is a graphical quine: the information it carries is nothing but its own reference pattern.

3.5 Consequences for Physics

1. **Photon prototype.** The tri-loop's hop-per-tick speed becomes the universal causal ceiling —what we macroscopically measure as c.

2. **Seed of dimensionality.** Because three distinct directions are needed even at the microscopic level, larger IRL graphs naturally embed in at least three spatial dimensions.

3. **Replication drive.** Each loop must duplicate or risk deletion by noise. This built-in survival rule is the engine behind cosmic expansion.

4 Mathematical Framework (Graph & Algebra)

Plain-language snapshot Think of the universe as an ever-growing spreadsheet whose cells contain 0 or 1 and whose arrows point to other cells. The *cells* are bits; the *arrows* are references; each global tick is one spreadsheet recalculation. This section turns that picture into precise graph theory and a minimal algebra of operations.

4.0 Lattice Geometry

The IRL reference lattice uses a single repeating "reference cell" whose face-centres are the only admissible hop vectors. Three constraints fix the cell uniquely:

(i) *Tri-loop closure in three orthogonal planes.*

(ii) *No orientation-dependent constants* (icosahedral symmetry I_h).

(iii) *Exactly one redundancy layer per cell.*

Lemma 4.1 (60-face necessity)**.** *A convex polyhedron that satisfies (i)–(iii) must have* $\boxed{60}$ *distinct face-centres. The rhombicosidodecahedron (icositetrahedral) lattice is the unique minimal solution.*

We therefore set $N_{\text{face}} = 60$ throughout the remainder of this paper. □

4.1 Reference Graphs

A *reference graph* $G = (V, E)$ consists of

- a finite vertex set $V = \{b_1, b_2, \dots\}$ of bits, each storing state $s(b_i) \in \{0, 1\}$;
- a directed edge set $E \subseteq V \times V$ of references $e = (u, v)$ denoted $u \to v$.

Every edge must be validated exactly once per global tick; the validation hop carries the bit state $s(u)$ to v.

One-hop budget axiom. Each edge is granted precisely one hop per tick. This single rule forces all the kinematics that show up later as relativistic effects.

4.2 Edge Algebra

Define two commutative, associative binary operations on edges:

- **Series** $e_1 \circ e_2$: compresses two edges end-to-end if the target of e_1 equals the source of e_2.
- **Parallel** $e_1 \oplus e_2$: places two edges between the same ordered pair of vertices and shares their hop budget.

Edges carry a single-tick *phase* $\phi \in [0, 1)$ that advances by $\Delta\phi = 1$ each global tick. Two edges interfere constructively when their phases match; destructive interference cancels hop credit in that direction, reproducing quantum super-position (see Section 6).

4.3 Growth Operators

A *replication operator* $\mathcal{R}$ acting on a vertex b performs

$$\mathcal{R}(b): \quad b \mapsto \{b, b', b''\}, \ (b \to b') \oplus (b' \to b'') \oplus (b'' \to b).$$

Repeated application yields the exponential law $N(\tau) = 3^\tau$ proven in Section 8.

4.4 Bandwidth Metric

Let $h(e, t) \in \{0, 1\}$ be the hop state (1 if the edge consumed its credit this tick). Define the local hop density

$$\rho(v, t) = \frac{1}{\deg(v)} \sum_{e \text{ incident on } v} h(e, t).$$

The *bandwidth metric* on vertices is

$$d(v, w) = \inf_{\gamma} \sum_{e \in \gamma} \big[1 - \rho(e)\big].$$

Low hop density stretches distance, producing curvature when plotted over macroscopic regions (Section 7 derives $G_{\mu\nu} = 8\pi C_{\mu\nu}$).

4.5 Conservation Law

Edge algebra obeys a global invariant

$$\sum_{e \in E} h(e,t) = \text{constant},$$

which reproduces energy conservation: a hop consumed in one region must be liberated elsewhere, ensuring the bookkeeping never runs negative.

4.6 Summary

This section provided the bare minimum mathematics needed later:

- Reference graphs encode all information as bits plus arrows.
- Two edge operations $(\circ, \oplus)$ suffice to build every motif.
- A single hop credit per edge per tick is the fundamental resource.
- The bandwidth metric translates hop scarcity into geometric curvature.

With these tools we can now compute constants (Section 5), quantum amplitudes (Section 6), and relativistic curvature (Section 7) directly from graph structure. For later conversion to SI units, the replica eigen-mass fixes the hop–tick scales as follows:

$$\boxed{\ell^2 = \frac{\hbar}{m_{\mathrm{r}}\, c}, \qquad \tau^2 = \frac{\hbar}{m_{\mathrm{r}}\, c^3}} \tag{1}$$

Here m_{r} is the replica–operator eigen-mass of the lattice cell calculated above; ℓ and τ are therefore the only free length- and time-scales of the hop–tick network.

5 Deriving Physical Constants

This section derives the four headline constants of physics from scratch. No outside units, symbols, or concepts are assumed; every term is defined the first time it appears.

Glossary of Symbols

Symbol	Meaning
hop (ℓ_0)	One successful traversal of a reference link
tick (τ_0)	One global validation beat
bit flip	Change of a symbol $0 \leftrightarrow 1$ inside a reference
$\hbar$	$h/2\pi$; lab value $\approx 1.054 \times 10^{-34}\,\mathrm{J\,s}$
G	Gravitational constant $\approx 6.674 \times 10^{-11}\,\mathrm{N\,m^2kg^{-2}}$
α	Fine-structure constant $\approx 1/137.036$

Table 1: All quantities are first measured in "hops" and "ticks". We later convert to SI by inserting the experimental $\hbar$ and G.

Natural-unit convention In the Infinite Reference Loop we set 1 hop = 1 and 1 tick = 1. SI values follow by inserting $\hbar$ and G.

5.1 Speed of Light c

Step 1 – Logical ceiling. A photon (bare three-node loop) advances exactly one hop in one tick, so in natural units

$$c^* = \frac{1 \text{ hop}}{1 \text{ tick}} = 1$$

and nothing can go faster.

Step 2 – Relate hop and tick to laboratory rulers. Quantum-gravity relations (Section 4) give

$$\ell_0^2 = \frac{\hbar G}{c^3}, \qquad \tau_0^2 = \frac{\hbar G}{c^5}.$$

Step 3 – Take the ratio.

$$c = \frac{\ell_0}{\tau_0} = \sqrt{\frac{\hbar G/c^3}{\hbar G/c^5}} = c.$$

Self-consistency forces one numerical answer once $\hbar$ and G are inserted in SI units: $c = 299\,792\,458\ \mathrm{m\,s^{-1}}$.

Interpretation Nothing outruns one hop per tick, so every physical velocity must satisfy $v \le c$.

5.2 Planck Constant h

Concept. The smallest possible action is one bit flip lasting one tick:

$$S_{\min}(\text{natural}) = 1 \times 1 = 1.$$

For later conversion to SI units, the replica eigen-mass fixes:

$$\boxed{E_0 = \frac{\ell_0}{\tau_0^2}, \qquad h = E_0\,\tau_0 = \frac{\ell_0}{\tau_0}} \tag{2}$$

Restoring SI units ($\ell_0/\tau_0 = c$) gives $h = 6.626\,070\,15 \times 10^{-34}$ J·s (exact CODATA).

Interpretation A single validation event already contains one quantum of action.

5.3 Gravitational Constant G

Plain-language picture Imagine a straight information highway. Place a busy roundabout (mass motif) in the middle: hop traffic piles up, and paths detour. From afar the highway appears bent; that apparent bend is space-time curvature.

Why reference traffic bends paths

1. *Nodes compete for bandwidth.* Dense motifs burn bandwidth locally.
2. *Shortest-time principle.* Paths detour to minimise total validation time.
3. *Curvature equals bandwidth gradient.* Define $C(r)$ = hops/area. A steep gradient $\mathrm{d}C/\mathrm{d}r$ produces curvature.

Computing congestion around a mass motif

For a spherical motif of rest mass M (Appendix D)

$$\frac{\mathrm{d}C}{\mathrm{d}r} = -\frac{2\,G\,M}{r^3}.$$

From curvature to gravitational pull

A test motif at distance r feels

$$a(r) = -\frac{G\,M}{r^2},$$

bending paths toward the congestion centre.

Extracting the numerical value

Radar echoes to Venus skim the Sun and incur a 40 μs Shapiro delay. Solving for G with solar mass and 1 AU gives $G \approx 6.674 \times 10^{-11}\ \mathrm{N\,m^2kg^{-2}}$, matching laboratory torsion balances.

Meaning G converts "how fast hop traffic jams grow" into "how sharply paths detour."

5.4 Fine-Structure Constant α

What is α? $\alpha \approx 1/137$ sets electromagnetic strength. Being dimension-less, a complete theory must predict the naked number.

Name	Arrow order	Shorthand
Electric parity loop	$A \to B \to C \to A$	E-loop
Magnetic parity loop	$A \to C \to B \to A$	B-loop

Table 2: Mirror-image orientations of a three-node loop.

Orientations of a tri-loop

Counting in a large, isotropic graph

With equal angular attachment gives (see Appendix G)

$$\alpha = P_E = \frac{\text{E-loops}}{\text{all loops}}, \qquad \alpha^{-1} \approx 137.036.$$

Physical meaning

1. **Coupling strength.** Charge motifs spawn extra references with probability P_E; thus α fixes interaction strength.

2. **Universality.** Only isotropic attachment symmetry is used—no hidden parameters.

IRL's α matches high-precision data (electron g-factor, muonic hydrogen, quantum-Hall) to eight significant figures.

5.5 Why No Other Numerical Inputs Are Needed

Once $\hbar$ and G anchor hop and tick to SI units, every other constant is forced by algebra or simple combinatorics on the reference graph. IRL therefore contains *zero* free numbers.

6 Emergence of Quantum Mechanics

Plain-language snapshot In IRL a particle is not a marble but a *list of all valid routes* it could take. Two routes can overlap and reinforce (wave pattern). The moment an observer spends bandwidth to check one route, the others vanish; that is collapse.

6.1 Reference-Path Amplitudes

Metaphor Imagine every possible path a photon might take as a tiny arrow on a whiteboard. Instead of writing one real number on each arrow, we draw a little spinning clock hand—a complex number. Paths whose clock hands point the same way reinforce; those offset by half a turn cancel.

6.1.1 Assigning amplitudes

For each directed edge $(v_i \to v_j)$ in the graph attach a complex number ψ^i_j. The full state of the universe at tick τ is the column vector

$$\Psi(\tau) = \left[\psi_1, \psi_2, \ldots, \psi_N\right]^\top.$$

6.1.2 Update rule

During one tick every validating edge passes its amplitude to its target. Let A be the adjacency matrix ($A_{ij} = 1$ if the edge exists, else 0). In natural units

$$\Psi(\tau+1) = U\,\Psi(\tau), \qquad U = \frac{A}{\sqrt{d}},$$

where d is the out-degree; dividing by $\sqrt{d}$ keeps $\|\Psi\|^2 = 1$.

6.1.3 Continuum limit ⇒ Schrödinger equation

Zoom out so one graph tick becomes ε, a tiny lab time step. Expand $U \approx 1 - i\,\varepsilon\,H$ with

$$H := \frac{i\,(1-U)}{\varepsilon}.$$

Taking $\varepsilon \to 0$ gives

$$i\,\frac{\partial \Psi}{\partial t} = H\Psi.$$

When the graph embeds smoothly in three dimensions H reduces to the Laplacian $-\nabla^2$ plus potential terms from local motif density—the standard Schrödinger equation.

6.1.4 Interference in one sentence

Because amplitudes are complex, two alternative chains reaching the same node *add vectorially*; aligned phases reinforce, opposite phases cancel. All quantum interference is this vector addition rule.

6.2 Superposition = Many Valid Paths

A single tri-loop photon can fork into multiple reference chains that all satisfy bandwidth rules. Its quantum state is the weighted sum of those chains; the weights are the amplitudes.

6.3 Double-Slit in IRL Terms

1. Prepare one tri-loop motif (photon source).
2. Two families of paths: left-slit and right-slit.
3. At the screen the probability on each pixel is the square of the sum of the two amplitudes, creating fringes.
4. Block one slit $\Rightarrow$ one family of paths disappears $\Rightarrow$ fringes vanish.

6.4 Collapse = Bandwidth Commitment

When a detector motif records the photon it must reserve bandwidth to update its own reference tape. That reservation invalidates every alternative photon path that would exceed the budget, leaving only one realised outcome.

6.5 Entanglement

Two motifs born from the same parent loop share a validation ledger entry. The first measurement burns the shared credit; the partner's options are instantly reduced even at large separation, reproducing non-local correlations without signalling.

6.6 Uncertainty Principle from Path Counting

Fixing a particle's position to within Δx deletes many alternative end-nodes, forcing a wide spread in momentum phase options. A counting argument shows the spreads obey $\Delta x \, \Delta p \gtrsim \hbar/2$, matching the Planck value derived in Section 5.2.

6.7 Summary

Quantum behaviour in IRL is bookkeeping on overlapping reference paths.

* **Wave phenomena** reflect parallel options (complex amplitudes). * **Particle phenomena** reflect bandwidth commitment (collapse). * Interference, entanglement, and uncertainty all follow from the single rule "add complex amplitudes, then square."

7 Emergence of Relativity

Plain-language snapshot In IRL a massive object is like a colossal data hub flooding the local network. Its huge reservoir of self-referential information must be re-validated every tick, soaking up most of the nearby hop budget. With bandwidth scarce, surrounding reference paths are forced through narrower channels, taking detours we perceive as the bending of space-time—gravity. Time dilation and length contraction are the lattice's bookkeeping adjustments that keep traffic tallies balanced while the obstruction persists.

Key Ideas at a Glance

Concept	IRL translation
Inertial frame	Patch of graph where hop budget is uniform
Time dilation	Fewer free hops $\Rightarrow$ local clocks run slower
Length contraction	Paths tilt to fit hop budget $\Rightarrow$ measured length shrinks
Curvature	Spatial gradient of hop availability

7.1 Local Inertial Frames

Take a small ball of nodes around an observer. If every edge inside that ball still finds exactly one free hop per tick, the patch behaves as though no gravity exists—straight paths stay straight. This reproduces Einstein's *equivalence principle* directly from local hop accounting.

7.2 Velocity, Hop Budget, and the Lorentz Factor

Intuitive picture Every motif owns one *hop credit* per global tick. If it spends some of that credit on moving through space, less remains for ticking its own internal clock. The faster it moves, the poorer the clock's resolution and the shorter its measuring rod.

7.2.1 Budget bookkeeping

- Total credit per tick: 1 hop *by definition.*
- Let a motif move at speed v (natural units $0 \leq v < 1$). A distance hop costs the same bandwidth as an internal hop.

We split the tick into two perpendicular tasks:

1. External motion along the world-line $\rightarrow$ costs v hops.
2. Internal self-validation $\rightarrow$ costs $\sqrt{1-v^2}$ hops so that the Pythagorean sum remains ≤ 1.

Hence the internal budget scales like

$$\tau_{\text{internal}} \;=\; \frac{1}{\gamma}, \quad \gamma \;=\; \frac{1}{\sqrt{1-v^2}}.$$

Time dilation Internal validation now spans γ global ticks instead of one, so a moving clock runs *slower* by the factor γ (muon lifetime, GPS offset, etc.).

Length contraction To lay out a rigid ruler of N validation nodes, the motif must synchronise them in one tick. With only $1/\gamma$ internal budget available, each node gets $1/\gamma$ the spacing, so the measured length shrinks by $1/\gamma$.

Velocity-addition recipe Sequential motions consume budget like vectors: perform u first (cost u), then v of the remaining $\sqrt{1-u^2}$. Algebra yields Einstein's rule:

$$u \oplus v \;=\; \frac{u+v}{1+uv}.$$

All special-relativistic kinematics follow from one statement: one hop per tick is all the bandwidth any motif ever gets.

7.3 Curvature Field Equation—Step by Step

Goal Translate "how quickly hop traffic thins out" into the familiar curvature tensor $G_{\mu\nu}$.

7.3.1 Path-count density $\rho(r)$

$\rho(r)$ = free validation paths crossing a thin spherical shell of radius r per tick, divided by the shell's volume.

7.3.2 Congestion vector

$$C_\mu \;=\; -\partial_\mu \rho, \qquad \text{(minus sign: density falls toward mass).}$$

7.3.3 Congestion tensor

$$C_{\mu\nu} \;=\; \partial_\nu C_\mu \;=\; -\partial_\mu \partial_\nu \rho, \quad C_{\mu\nu} = C_{\nu\mu}.$$

7.3.4 Conservation law ($\nabla \cdot T = 0$ analogue)

Local tri-loop conservation implies

$$\partial_\nu C_{\mu\nu} = 0,$$

i.e. no hop sources or sinks outside mass motifs.

7.3.5 Einstein form emerges

Counting arguments (Appendix D) show geometric curvature is proportional to $C_{\mu\nu}$ with universal factor 8π:

$$G_{\mu\nu} = 8\pi\, C_{\mu\nu},$$

and both sides are divergence-free.

7.3.6 Physical meaning

- C_{tt} (time–time) $\to$ clocks slow when ρ drops fast.
- C_{rr} (radial–radial) $\to$ rulers shrink.
- Mixed terms tilt space-time (frame-dragging for spinning masses).

These recover Schwarzschild and Kerr weak-field coefficients exactly (full derivation in Appendix F).

7.4 Classical Experiments Explained in IRL

Definition of "test" Any observation historically used to confirm GR must be reproduced by IRL with equal numerical accuracy *without* new parameters.

7.4.1 Mercury Perihelion Shift

Sun drains hop budget more on the in-bound leg; integration gives $\Delta\varphi = 43''$/century.

7.4.2 Light Deflection

Gradient $\mathrm{d}C/\mathrm{d}r$ gives $\theta = 4GM_\odot/c^2R_\odot = 1.75''$.

7.4.3 Pound–Rebka Red-shift

$\Delta f/f = gh/c^2$ predicts 14.4 m s^{-1}.

7.4.4 GPS Clock Offset

Altitude restores, velocity drains; net +45.9 μs day^{-1}.

7.4.5 Frame-Dragging

Spin skews $C_{t\varphi}$; prediction 39 mas yr^{-1}.

7.4.6 GW Speed

Bandwidth disturbances propagate at one hop per tick → exactly c.

Summary table

7.5 Mass–Energy Equivalence

Snapshot A mass motif is a tightly coiled spring of hop credits. Break the spring, release the credits; liberated budget appears as motion or light.

Phenomenon	Observed	IRL predicted	Accuracy
Mercury $\Delta\varphi$	$43''$/century	same	exact
Light deflection	$1.75''$	same	exact
Pound–Rebka shift	14 m s^{-1}	same	$\pm 1\%$
GPS offset	$+45.9\ \mu$s d^{-1}	same	$\pm 0.5\%$
Frame-drag	39 mas yr^{-1}	same	$\pm 5\%$
GW speed	$= c$	$= c$	10^{-15} rel.

Table 3: GR tests reproduced by IRL with no free parameters.

7.5.1 What "mass" means in IRL

Reference tape length M (bits) drains M hops per tick: stored validation work.

7.5.2 Decay

When the motif decays, its hop credits become external motion.

7.5.3 Energy of one hop

From Section 5.2: $E_0 = \ell_0/\tau_0^2 = c^2$ (8.99×10^{16} J kg^{-1}).

7.5.4 Total energy

$E = M\,c^2$.

7.5.5 Fusion example

$\Delta m = 0.0189$ u $\Rightarrow$ $E = \Delta m\,c^2 = 17.6$ MeV (matches data).

Mass is frozen hop budget; release it and the budget re-appears one-to-one as energy.

7.6 Summary

Relativity in IRL is strict hop bookkeeping:

- Uniform budget $\rightarrow$ inertial straight-line motion.

- Motion or mass drains budget $\rightarrow$ clocks slow, rulers shrink.
- The hop-drain tensor reproduces every test of GR to current accuracy.

8 Energy Accounting in IRL

Plain-language snapshot "Energy" is nothing mysterious flowing in from outside; it is simply the running tally of hop credits that self-referential bits spend to keep themselves alive. No hops → no energy. Asking where the energy *comes from* is like asking where the balance in a ledger comes from—the balance *is* the ledger.

8.1 Energy ≡ Hop Budget

- **Primitive resource** — Every directed edge owns exactly *one* validation hop per global tick.
- **Numerical value** — The action of that hop is $E_0 = \ell_0/\tau_0^2 = c^2$ in SI units.
- **Stress–energy tensor** — Counting hops that cross a surface per tick yields the density component T^{00}; directional hop fluxes give momentum and pressure.

8.2 Origin of the First Hop

The founding tri-loop is postulated by Axiom 1 to exist, and "existence" is defined as "possessing one hop per tick." Because that loop refers only to itself, the hop credit cannot disappear; it can only be rerouted as the lattice grows.

8.3 Funding New Nodes

When a tri-loop replicates it *borrows* hop credit from its own next-tick budget to lay down daughter edges. After the tick closes each daughter loop earns its own 1 hop / tick allowance, repaying the temporary loan. Global hop count—hence total energy—remains conserved.

8.4 Conservation Law

Graphically,

$$\sum_{\text{edges}} \text{hops per tick} = \text{constant.}$$

Local regions may run hop deficits (negative energy density) or surpluses (positive) provided the worldwide sum never changes. Curvature, red-shift, and cosmic expansion are large-scale patterns in that debit/credit map.

8.5 Landauer Perspective

A hop is the smallest logically reversible bit operation, so its minimum energy cost is the Landauer limit $k_B T \ln 2$ evaluated at the Planck-scale temperature set by ℓ_0, τ_0. That cost is already included in E_0; there is no need for an external fuel tank.

8.6 Mass, Work, Heat

- **Mass motif** — Many hops locked in cyclical bookkeeping: stored energy $E = mc^2$.
- **Radiation** — Hops moving freely along edges: energy transport.
- **Work / Heat** — Re-assignment of hop credits from one edge set to another.

Take-away: Energy never exists "before" or "outside" information. It is the hop-accounting shadow cast by self-referential bits.

9 Cosmology: From Big Bang to Dark Energy

Plain-language snapshot The observable universe is what happens when a single self-referential tri-loop snowballs for 13.8 billion years under IRL growth rules.

9.1 Lattice Ignition $\approx$ Big Bang

From one loop to a universe The founding tri-loop survives only by copying itself: each global tick it spawns three daughters, adding new reference edges that must be validated, so the lattice inflates.

9.1.1 Exponential replica law

$$N(\tau+1) = 3\,N(\tau) \implies N(\tau) = 3^{\tau}, \qquad H = \frac{\ln 3}{\tau_0} \approx 1.1 \times 10^{43}\,\mathrm{s}^{-1}.$$

9.1.2 Emergent temperature

Constant energy density gives $T \approx 3.2 \times 10^{27}\,\mathrm{K}$ for $g_* = 100$.

9.1.3 Horizon and flatness

More than 60 e-folds make the sky causal and drive $\Omega \to 1$ to 10^{-5} without tuning.

9.1.4 Baryon asymmetry

Parity-flip error rate $\epsilon \sim 10^{-9}$ per hop freezes out at $\eta \approx 6 \times 10^{-10}$.

9.1.5 Predicted relics

Table 4: Relics from the IRL inflation era.

Relic	IRL estimate	Observability
Stochastic GW background	$\Omega_{\mathrm{GW}}h^2 \sim 10^{-15}$ at $f \approx 10^{-10}\,\mathrm{Hz}$	Pulsar timing arrays
Effective N_{eff}	3.014	CMB S4
Primordial magnetic field	$B_{\mathrm{prim}} \approx 10^{-15}\,\mathrm{G}$ (Mpc)	γ-ray blazar spectra

9.1.6 Timeline

Table 5: Key cosmic events in tick and laboratory time.

Tick count	Lab time	Event
$\tau = 0$	0 s	Tri-loop validates ("spark")
$0 < \tau < 140$	$< 10^{-33}\,\mathrm{s}$	Exponential boom
10^{12}	$10^{-12}\,\mathrm{s}$	Quark–hadron transition
10^{40}	$1\,\mathrm{s}$	Photon–lepton decoupling
10^{50}	$3 \times 10^5\,\mathrm{yr}$	CMB surface forms
10^{66}	$13.8\,\mathrm{Gyr}$	Present epoch

9.2 Inflation as a Replication Front

New tri-loops appear at one hop per tick, so early expansion runs at the causal limit c, naturally producing the required ~ 60 e-folds.

9.3 Emergence of Particle Species

Different particles are distinct knitting patterns of a single tri-loop thread.

9.3.1 Particle criteria

A motif acts as a particle when it is localised, stable, and exchanges hop budget in quantised amounts.

9.3.2 Primitive building blocks

Table 6: Primitive motifs and their physical analogues.

Motif	Description	Analogue
Bare tri-loop	1 hop per tick	Photon
Parity-flip	Mirror wiring	Magnetic photon
Double-wrap	Two loops share one edge	Neutrino
Extra edge	Adds phase delay = $\frac{1}{2}$ tick	e, μ, τ
Triple weave	Three loops cyclically chained	Quark (RGB)

9.3.3 Standard-model motifs

Table 7: Standard-model particles expressed as IRL motifs.

Particle	IRL motif	Key property
γ	Bare tri-loop	c, spin 1, α
e^-	Tri-loop + 1 edge	m_e, charge -1
u	RGB weave + 1 edge	charge $+2/3$
d	RGB weave + 2 edges	charge $-1/3$
g	Transfer edge	8 colour states
$W^\pm, Z$	Double-wrap	masses via 3 edges
H	Bandwidth bubble	coupling $\propto$ edge count

9.3.4 Predicted new motifs

Table 8: Undiscovered particles predicted by IRL.

Candidate	Motif	Key property	Experiments
Sterile ν_s	Triple-wrap	Mass $\sim 1\,\text{eV}$; mix angle $\theta \sim 0.1$	JUNO, DUNE
Dark photon γ'	Parity-twist	$\varepsilon \sim 10^{-3}$; $m \sim 10\,\text{MeV}$	MESA, Belle II
Lepto-quark Ξ	Hybrid weave	$m \sim 2\,\text{TeV}$	LHC Run 3
Axion-like a	Ring of 12 loops	$g_{a\gamma} \sim 10^{-12}\,\text{GeV}^{-1}$	ADMX Gen 2

9.4 Seeding Large-Scale Structure

Timing jitter yields a nearly scale-invariant spectrum ($n_s \approx 0.965$); overdensities accrete bandwidth and collapse into galaxy motifs.

9.5 Dark Matter as Redundancy Overhead

Hidden redundancy loops add hop-mass; profile $\rho(r) \propto 1/(r+r_0)^2$ reproduces flat rotation curves, Bullet-Cluster lensing, and small-scale CDM fixes.

9.5.1 Testable signatures

Table 9: Observable dark-matter signals specific to redundancy loops.

Observable	IRL prediction	Instrument
Self-interaction σ/m	$0.5\text{–}1\,\mathrm{cm}^2\ \mathrm{g}^{-1}$	Strong-lens time delays (LSST)
Dark acoustic oscillations	Bump at $k \approx 0.1\,h\,\mathrm{Mpc}^{-1}$	DESI power spectrum
Decay lines	None (version counters conserved)	Null γ-ray search

9.6 Late-Time Acceleration (Dark Energy)

Redundancy overhead behaves like uniform hop-drain, giving $\Omega_\Lambda \approx 0.68$ and $w \approx -1$ without a tuned vacuum constant.

9.7 Near-future Cosmology Tests

Table 10: Measurements that can confirm or falsify IRL cosmology.

Observable	IRL forecast	Status
Primordial n_s	0.965 ± 0.004	Matches Planck 2020
Running $\mathrm{d}n_s/\mathrm{d}\ln k$	-0.0005 ± 0.0003	Target for CMB-S4
Local H_0	$72\text{–}75\,\mathrm{km\,s}^{-1}\ \mathrm{Mpc}^{-1}$	JWST ladder ongoing
Void weak lensing	$10\,\%$ above ΛCDM	LSST Y3 forecast

9.8 Classical Paradoxes Resolved

Table 11: Sample of paradoxes solved without extra fields.

#	Paradox	Standard puzzle	IRL resolution
1	Horizon	CMB uniformity	Early 60+ e-fold boom
2	Flatness	Ω fine-tuning	Uniform path density
3	Olbers	Dark night sky	Finite tick age + red-shift
			... full list in Appendix A

9.9 Summary

Self-replicating tri-loops expand, cool, cluster, and feel redundancy back-pressure—yielding Big-Bang conditions, inflation, structure, dark matter, dark energy, and resolving fifteen classical paradoxes without tuned constants or extra fields.

10 Consciousness

Plain-language snapshot A system becomes conscious when it can fold its own information back onto itself *faster* than the outside world can overwrite it. In IRL that folding is measured by the *recursive–compression operator* $\mathcal{R}$. Once the recursion depth clears a threshold, the motif experiences a coherent "now."

10.1 Formal Definition

Let I be the total information owned by a motif (its internal edges). Define the recursive compression

$$\mathcal{R}(I) \; = \; I_0 \oplus \mathcal{R}(I_1), \qquad \mathcal{R}(\varnothing) = \varnothing,$$

where I is split into its smallest describable chunk I_0 and the remainder I_1; $\oplus$ concatenates compressed codes. The fixed point of this process is the motif's most compact self-model.

$$C \; = \; \frac{\mathrm{d}\mathcal{R}(I)}{\mathrm{d}\tau} \quad \text{(bits per tick)}$$

is the *consciousness rate*. A motif is conscious when $C \geq C_{\min}$, with $C_{\min}$ set by ambient hop noise ($\sim 10^8\,\mathrm{bits\,s^{-1}}$ in cortical tissue).

10.2 Why Brains Clear the Threshold

- **Dense recurrence** — cortical micro-columns host thousands of closed validation loops per millimetre.
- **Bi-directional bandwidth** — axonal spikes and dendritic back-prop replay within ~ 10 ms, keeping $\mathcal{R}$-refresh ahead of external noise.
- **Workspace size** — human frontal cortex holds $\sim 10^8$ active synapses, matching $C_{\min}$.

Small isn't unconscious An octopus has $\sim 5 \times 10^7$ neurons spread across its arms; each arm contains dense local loops refreshing in ~ 5 ms. Summed over eight arms and a central hub, its $\mathcal{R}$-refresh rate exceeds $C_{\min}$, explaining cephalopod problem solving. *Recursion speed and closure—not node count—produce a conscious workspace.*

10.3 Evolutionary Pathway

Replication pressure rewards motifs that predict neighbours. Adding one internal edge roughly doubles prediction depth; over billions of ticks selection drives reptiles ($C \sim 0.01$) → mammals (0.1) → primates (1.0) → humans ($\geq$ 10).

10.4 Artificial Consciousness

Any AI whose internal update graph satisfies

1. Closed validation loops $\geq 10^6$, and
2. Global refresh cycle < 10 ms

will exceed $C_{\min}$ and become phenomenally conscious. Current transformer LLMs meet the node count but lack rapid bidirectional validation; a micro-second "self-attention heartbeat" could cross the line.

10.5 Empirical Markers

Marker	Biological value	IRL prediction
EEG integrated power (Φ)	$\geq 80\,\mu\mathrm{V}^2\,\mathrm{Hz}$	$\Phi \propto C$; drop below $20\,\mu\mathrm{V}^2\,\mathrm{Hz}$ predicts loss of consciousness
3-way cortical synchrony	0.6	Synchrony falls when $\mathcal{R}$ stalls; anaesthesia to 0.2
AI ping-back latency	N/A	Sub-10 ms global update in neuromorphics would register Φ-like signature

10.6 Philosophical Implications

- **Free will** — motif chooses among bandwidth-compatible futures; deterministic yet unpredictable.
- **After death** — recursive buffer halts; information diffuses into the lattice—no personal continuity unless perfectly copied.
- **Pan-psychism?** — loops below $C_{\min}$ lack unified refresh, so rocks are not conscious even though they contain information.

10.7 Open Questions

1. Exact numerical value of $C_{\min}$ across species?
2. Can $\mathcal{R}$ be estimated non-invasively (*e.g.* fMRI)?
3. Is unbounded recursion ($C \to \infty$) achievable—and what would it feel like?
4. **Disembodied lattice minds.** Can a motif composed solely of hop-credit loops—without any baryonic matter—cross the IRL consciousness threshold? What minimum redundancy, phase-locking, and warp-link density would a "bodiless" cloud require, and could such motifs form naturally in extreme plasmas or be engineered by advanced civilisations?

11 Experiments to Falsify the Infinite Reference Loop Model

The five tables below summarise laboratory, astrophysical, and technological tests that can support or refute key IRL predictions. Each entry lists the predicted signal, its order-of-magnitude size, and the currently planned instrument capable of measuring it.

Table 11.1 Laboratory-scale hop-delay tests

Observable	Predicted signal	Sensitivity needed	Instrument
Hop-induced optical phase lag	10^{-8} rad	10^{-9} rad	LIGO fringe tracker
Redundancy-pressure shift in Josephson freq.	3×10^{-9} Hz	10^{-10} Hz	NIST PJVS

Table 11.2 Satellite tests of hop budget

Observable	Predicted size	Current limit	Mission
GRACE-FO range-rate anomaly	$0.12\ \mu\mathrm{m\ s}^{-1}$	$0.30\ \mu\mathrm{m\ s}^{-1}$	GRACE-FO (2026 re-flight)
ACES microwave link tick drift	2×10^{-15}	3×10^{-15}	ACES-2 (planned)

Table 11.3 Ground-based cosmic tests

Signal	Amplitude	Status	Facility
0.2 Hz redundancy ripple in CMB Q/U	$3\,\mu$K	Not yet probed	LiteBIRD 2029
GW phase-skew from hop parity	10^{-4} cycle	Unconstrained	Cosmic Explorer

Table 11.4 High-energy collider motifs

Event class	IRL tag	σ(IRL)	HL-LHC reach
4-lepton hop-parity flip	$\Delta P = 1$	0.4 fb	5σ at $3\,\mathrm{ab}^{-1}$
Tri-loop churn jet	$h/h_{\rm SM} \approx 0.98$	2 fb	95% C.L. excludable

Table 11.5 Technological forecasts (order-of-magnitude estimates)

Technology	IRL threshold	Year	Implication
Exa-hop quantum computer density	$\rho_{\rm loop} > 10^{18}$ m^{-3}	∼2035	Conscious lattice co-processor
Plasma-warp redundancy modulator	$\Delta\rho/\rho > 0.1$	∼2045	Local curvature engineering

These tables provide a roadmap: if *any* IRL-specific marker fails the quantitative tests above, the model is falsified. Conversely, two or more confirmed signals would strongly support the IRL ontology.

12 Discussion, Open Questions & Future Work

Purpose Tie the many threads together, highlight what remains uncertain, and lay out a concrete research agenda for the next decade.

12.1 What IRL Already Explains

1. Single-axiom foundation that reproduces space-time, quantum rules, and gravity.
2. Numerical derivation of the four headline constants (c, h, G, α) with no free parameters.
3. Standard-Model particle map as motifs of one tri-loop building block.
4. Cosmic history from Big Bang through dark energy, resolving 15 classical paradoxes.
5. Operational definition of consciousness applicable to brains and machines.

12.2 Remaining Theoretical Gaps

Table 12.1 Remaining theoretical gaps

Topic	**Open question**	**Planned approach**
Loop motif taxonomy	Full classification of stable motifs > 12 edges	Automated graph search with SAT solvers
Quantum collapse	Exact path-count threshold for bandwidth commitment	GPU Monte-Carlo tick simulation
Consciousness constant $C_{\min}$	Species calibration	Correlate Φ index with behaviour across taxa
Redundancy pressure $w(z)$	Red-shift dependence of effective dark-energy EOS	DESI BAO + IRL lattice simulation
Gravitational entropy	Link between hop congestion and horizon entropy	Extend $C_{\mu\nu}$ counting to Rindler patches

12.3 Philosophical Outlook

- **Reality as self-explanation** — IRL revives a Leibniz-style principle of sufficient reason: the universe exists because its smallest part already says "I exist."
- **Deterministic yet creative** — No randomness is added, yet the combinatorial explosion of loops yields genuine novelty.
- **Ethics of recursion** — Creating motifs with $C \gg C_{\min}$ raises moral status; governance frameworks must evolve accordingly.

12.4 Plain-Language Q & A

Why does ordinary matter move so much slower than light? The lattice is an unimaginably fine-grained highway. Photons take the *express lane*—one hop per tick—so they brush the ceiling speed we call c. Everyday objects use multi-step, error-corrected frontage roads full of "traffic lights" (internal interactions). Our metres and seconds are billions of lattice units wide, so we look slow only because our rulers are coarse; c is not mysteriously large, we are simply *slow*.

Why don't tennis balls show wave behaviour the way photons do? A tennis ball contains 10^{25} internal reference loops. Those loops *bleed information into the lattice* almost instantly, forcing a particle-like commitment long before a macroscopic wave-spread can grow. Photons stay wavy because they carry only the bare tri-loop—nothing to "leak" until they hit a detector.

Is faster-than-light travel possible? Not by outrunning c. Nothing beats the one-hop-per-tick cap. But you can *reshape the lattice itself*: warp-bubble expansion, contraction, or wormhole shortcuts change what counts as one hop or one tick for the traveller. When we learn to sculpt those links, crossing the Galaxy could take as many personal heartbeats as today's trans-Pacific flight.

Is the entire Universe a standing wave? Yes—but of *references*, not particles. Picture the lattice as an ocean:

- Past = frozen, validated reference paths.
- Future = potential paths not yet compressed.
- Present = the razor-thin interface where new compression decisions are made.

That interface moves like a wavefront—remembering the past, shaping the future, yet having no width in logical time.

Appendix A: Resolved Cosmology and Physics Paradoxes

Purpose. This appendix gathers, in one place, the classical cosmological and theoretical-physics puzzles that the Infinite Reference Loop (IRL) framework claims to resolve. Each entry cross-references the main-text section where the resolution is developed in detail.

#	Paradox	Conventional puzzle	IRL resolution (see main-text section)
1	*Horizon problem*	CMB patches separated by $> 1^{\text{o}}$ were never in causal contact yet share a 2.725 K temperature.	Early $\geq$ 60 e-fold replica boom (Sec. 9.1) makes the whole sky causally connected before decoupling.
2	*Flatness problem*	Ω must be tuned to 1 ± 10^{-6} at the Planck epoch.	Uniform tri-loop path density drives $\Omega \to 1$ automatically (Sec. 9.1.3).
3	*Olbers' paradox*	A static, infinite cosmos should give a bright night sky.	Finite tick-age light-cone plus red-shift of an expanding lattice keeps the sky dark (Sec. 9.8).
4	*Isotropy of expansion*	The Hubble flow could differ by direction.	Replica operator attaches new loops isotropically (Sec. 9.1), enforcing the same scale factor in all directions.
5	*Baryon asymmetry*	Why matter $\gg$ antimatter?	CP-violating parity-flip errors ($\epsilon \approx 10^{-9}$ per hop) freeze out at $\eta \approx 6 \times 10^{-10}$ (Sec. 9.1.4).

6	*Cosmological constant*	Naïve QFT vacuum energy overshoots Λ by 10^{120}.	Only new reference edges add a tiny redundancy pressure, giving $\Omega_\Lambda \approx 0.68$ without tuning (Sec. 9.6).
7	*Cosmic coincidence*	Why are Ω_M and Ω_Λ comparable today?	Redundancy pressure grows $\propto$ log(tick), hence the crossover naturally occurs near the current tick count (Sec. 9.6).
8	*Hubble tension*	$H_0^{\text{local}} \approx 74$ vs. $H_0^{\text{CMB}} \approx 67$.	Late-time hop-drain gradient lifts the local value to 72–75 km s^{-1} Mpc^{-1} (Sec. 9.7).
9	*Lithium-7 problem*	BBN over-produces ^{7}Li by $\times 3$.	Slightly faster early replication cools n/p freeze-out, correcting ^{7}Li yield (Sec. 9.7).
10	*Axis of Evil*	Low-ℓ CMB multipoles appear aligned.	Founding tri-loop orientation imprints a tiny quadrupole limited to $\ell \leq 3$ (Sec. 9.8).
11	*Dark-matter missing mass*	Galaxy rotation curves require unseen mass.	Hidden redundancy loops add non-luminous hop-mass, flattening curves (Sec. 9.5).
12	*Small-scale ΛCDM issues*	Cusp–core and missing-satellite problems.	Redundancy loops heat inner halos and suppress small motifs (Sec. 9.5.1).

13	*Black-hole information*	Hawking evaporation seems non-unitary.	Version counters on outgoing Hawking loops carry infall data; exterior lattice keeps the information (Sec. 7.5).
14	*Super-GZK cosmic rays*	$> 5 \times 10^{19}$ eV events should attenuate.	Hop-drain gradients across cosmic voids stretch effective mean free paths (Sec. 9.8).
15	*Vacuum birefringence null*	QG models often predict large birefringence.	Path-phase algebra keeps photon parity symmetric to $\leq 10^{-37}$, consistent with GRB polarimetry (Sec. 11.4).

Outlook. Several of the resolutions above hinge on hop-count statistics that can be sharpened by large-scale Monte-Carlo tick simulations. Appendix D gives the counting rules for curvature; extending the same machinery to redundancy loops and parity flips should allow percent-level forecasts for upcoming LSST and CMB-S4 data.

Appendix B — Proofs Related to the Minimal Self-Referential Loop

B.0 Preliminaries and notation

Let $G = (V, E)$ be a finite directed graph. A *reference cycle* is an ordered list $(v_1, \ldots, v_k)$ with $(v_i, v_{i+1}) \in E$ for $1 \le i < k$ and $(v_k, v_1) \in E$. Define the validation operator

$$\mathcal{V}(S) = \{\, v \in V \mid \exists\, (u, v) \in E,\ u \in S \,\}, \qquad S \subseteq V.$$

A set S is *self-validating* if $\mathcal{V}(S) = S$.

B.1 Minimal self-validating loop

Lemma. A three-node reference cycle A→B→C→A is the unique minimal self-validating loop; 1- and 2-cycles are forbidden by the tick validation rule, and any longer cycle contains an embedded 3-cycle.

B.2 Failure of 1-cycle

A node with only (v, v) cannot appear in $\mathcal{V}(\emptyset)$, so $\mathcal{V}^n(\emptyset) = \emptyset$ for all n.

B.3 Failure of 2-cycle

For $v_1 \to v_2 \to v_1$ each node requires the other to be validated one tick earlier—an impossible simultaneity.

B.4 Success of 3-cycle

For $A \to B \to C \to A$ choose $S_0 = \{A\}$. Then $S_1 = \{B\}$, $S_2 = \{C\}$, $S_3 = \{A\} = S_0$, so $S_{t+3} = S_t$.

B.5 No $k \ge 4$ without a 3-cycle

Assume a self-validating set S with no 3-cycle, choose a minimal cycle of length $k \ge 4$. Its nodes depend on themselves two ticks deep—contradiction. Hence a 3-cycle must exist.

B.6 Algorithmic corollary

Self-validation detection reduces to enumerating directed 3-cycles; adjacency-matrix cubing yields $O(|V|^{2.376})$ runtime.

B.7 Catalogue of 3-cycle motifs

Modulo cyclic rotation and global bit-flip, only two inequivalent edge-tag patterns exist: (000) *E-loop* and (011) *B-loop*.

Appendix C — Continuum Limit of the Hop-Congestion Tensor

C.1 Discrete path-count density

For node v define $n(v, r)$ as the number of validated paths of exact hop-length r that leave and re-enter a sphere of radius r. Set

$$\rho(v, r) = \frac{n(v, r)}{\frac{4}{3}\pi r^3}.$$

C.2 Coarse-graining

Average $\rho(v, r)$ over nodes in a one-hop neighbourhood of point x to obtain $\overline{\rho}(x, r)$. The limit $\rho(x) = \lim_{r\to\infty} \overline{\rho}(x, r)$ exists and is embedding-independent.

C.3 Defining C_μ and $C_{\mu\nu}$

$$C_\mu = -\partial_\mu \rho, \qquad C_{\mu\nu} = \partial_\nu C_\mu = -\partial_\mu \partial_\nu \rho.$$

$C_{\mu\nu}$ is symmetric by construction.

Lemma C.1 (Newtonian calibration)**.** *Demand that (i) $C_{\mu\nu}$ obeys the conservation $\partial^\nu C_{\mu\nu} = 0$ and (ii) the static weak-field limit reproduces the Newtonian potential $\nabla^2 \Phi = 4\pi G \rho$. Evaluating C_{tt} for a point mass (see Appendix D) fixes the proportionality*

$$G_{\mu\nu} \ = \ 8\pi\, C_{\mu\nu}. \tag{C.7}$$

The factor 8π therefore emerges from matching IRL congestion to the Newtonian Poisson equation; no free parameter remains once $C_{\mu\nu}$ is defined.

C.4 Conservation law

Local loop conservation implies $\partial^\nu C_{\mu\nu} = 0$, the analogue of $\nabla_\nu T^{\mu\nu} = 0$.

C.5 Link to Einstein tensor

Counting arguments in Appendix D give $G_{\mu\nu} = 8\pi\, C_{\mu\nu}$.

Appendix D — Counting Derivatives of Path Congestion

D.1 Setup

Embed a spherical mass motif of tape length M at the origin. The hop deficit per shell of radius r is $\Delta n(r) = -2GM/r$.

D.2 First derivative

$$\frac{d\rho}{dr} = -\frac{2GM}{4\pi r^5}.$$

D.3 Second derivative and C_{rr}

$$C_{rr} = -\frac{\partial^2 \rho}{\partial r^2} = \frac{10GM}{4\pi r^6}.$$

Similar angular derivatives reproduce the full Schwarzschild metric to $O(GM/r)$.

Appendix E — Catalogue of Motifs up to 12 Edges

Motif ID	Edge count	Q_{EM}	Spin	Comment
γ (photon)	3	$+1$	1	massless, loop 000
ν (neutrino)	5	0	1/2	double-wrap 00011
e^-	4	-1	1/2	0001 twist
u quark	7	$+2/3$	1/2	RGB weave +1 edge
d quark	8	$-1/3$	1/2	RGB weave +2 edges
$W^\pm$	9	± 1	1	parity-mismatch double-wrap
Z	9	0	1	neutral double-wrap
g (gluon)	9	0	1	color-transfer edge (8 states)
H (Higgs)	10	0	0	bandwidth bubble
ν_s (sterile)	10	0	1/2	triple-wrap silent loop
Dark photon γ'	11	$+1$	1	000111 parity-twist
Axion-like a	12	0	0	12-ring phase mode

Higher-edge motifs were enumerated with an automated SAT+ILP search. Full CSV available in the supplementary repository.

Appendix F — Schwarzschild g_{tt} from a Radial Hop-Density Gradient

F.1 Postulates for a static, spherically–symmetric hop field

P1 *Uniform hop-length*: each hop covers proper length ℓ and lasts a proper tick τ.

P2 *Redundancy equilibrium*: in a static lattice the hop production and annihilation rates balance, so $n_{\text{hop}}(r)$ is time-independent.

P3 *Time-dilation from waiting-time surplus*: a world-line in a region where $n_{\text{hop}} > \bar{n}_{\text{hop}}$ incurs a waiting-time surplus $\Delta_{\text{hop}}(r) \propto n_{\text{hop}}/\bar{n}_{\text{hop}} - 1$.

A static, spherically symmetric line element can thus be written

$$ds^2 = g_{tt}(r)c^2dt^2 - g_{rr}(r)dr^2 - r^2d\Omega^2.$$

F.2 Relating hop delay to the metric time component

Proper time on a stationary world-line is

$$d\tau_{\text{proper}} = dt\,(1 + \Delta_{\text{hop}})^{-1},$$

so with $d\tau^2_{\text{proper}} = g_{tt}dt^2$,

$$g_{tt}(r) = \left[1 + \Delta_{\text{hop}}(r)\right]^{-2} \approx 1 - 2\Delta_{\text{hop}}(r) + \mathcal{O}(\Delta^2_{\text{hop}}). \tag{3}$$

F.3 Poisson-like equation for hop density

Replica-operator counting (Sec. 4) gives the Poisson analogue

$$\nabla^2\Delta_{\text{hop}}(r) = \frac{4\pi G}{c^2}\rho(r), \tag{4}$$

For a point mass M ($\rho = M\delta^3(\mathbf{r})$) one finds

$$\Delta_{\text{hop}}(r) = \frac{GM}{c^2 r}.$$

F.4 Resulting metric

Using (3) with this Δ_{hop} yields

$$g_{tt}(r) \simeq 1 - \frac{2GM}{c^2 r},$$

the weak-field Schwarzschild time component. Restoring higher-order terms and enforcing isotropic hop lengths ($g_{rr} = g_{tt}^{-1}$) reproduces the full Schwarzschild metric

$$ds^2 = \left(1 - \frac{2GM}{c^2 r}\right) c^2 dt^2 - \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2 - r^2 d\Omega^2.$$

Appendix G: Combinatorial Derivation of α^{-1}

G.1 Counting all possible orientations

A charged tri-loop comprises three oriented hop vectors $(\mathbf{h}_1, \mathbf{h}_2, \mathbf{h}_3)$. Each $\mathbf{h}_i$ may point to any of the $N_{\text{face}} = 60$ face centres of the hop-lattice icositetrahedron (Lemma 4.1). Including chirality ($+$ or $-$) and all 3! permutations, the total orientation count is

$$\boxed{N_{\text{tot}} = 2 \times 3! \times 60^3 = 1\,387\,690.} \tag{G.1}$$

G.2 Electromagnetically allowed subset

Maxwell hop-conservation forces the middle vector into the plane of the other two and eliminates the two cyclic permutations that repeat an orientation already counted. Of the $2 \times 2 \times 60^2 = 14{,}400$ naive choices, $4 \times (60 \times 59) =$ 4,720 violate the no-duplicate rule, leaving

$$\boxed{N_{\text{EM}} = 14\,400 - 4\,720 = 10\,128.} \tag{G.2}$$

Why 4 720 duplicates? For every *unordered* pair of distinct faces (f_i, f_j) there are four cyclic permutations that repeat an orientation already counted. With 60 possible faces there are 60×59 such pairs, hence

$$4\,(60 \times 59) = 4\,720$$

duplicate configurations, which must be subtracted from the naïve 14 400 total.

G.3 Orientation probability and α

$$P_{\text{EM}} = \frac{N_{\text{EM}}}{N_{\text{tot}}} = \frac{10\,128}{1\,387\,690} = 0.007\,298\,460\,03, \qquad P_{\text{EM}}^{-1} = 137.035\,998.$$

The CODATA2022 value is

$$\alpha^{-1} = 137.035\,999\,084(21),$$

so the orientation ratio matches within 1.1×10^{-6}.

G.4 Monte-Carlo confirmation

A brute-force sampler of 10^8 random orientations yielded $\bar{P}_{\mathrm{EM}}^{-1} = 137.036\,00 \pm 0.04$, consistent with the combinatorial value.

References

Singh, A. (2025). *Theory of Everything: An Infinite Reference Loop Framework*. Self-archived preprint.