

Recognition Science: A First-Principles Introduction

Jonathan Washburn

Austin, Texas

jon@recognitionphysics.org

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Abstract

Why is there something rather than nothing? Recognition Science answers that long-standing question by replacing the usual ontology of “objects obeying laws” with a single bookkeeping rule: every act of distinguishing A from $\neg A$ creates a *recognition link* whose cost is $J(X) = \frac{1}{2}(X + 1/X)$. A perfectly empty ledger cannot acknowledge its own emptiness without contradicting that rule, so at least one unpaired link must appear. The cheapest self-consistent way to cancel the resulting imbalance is a golden-ratio self-dual lattice whose expansion manifests as space, energy, and curvature. Time is nothing more than the ordered queue of cost repayments; gravity is the backlog of unpaired costs; photons are debt-removal packets; and the observed constants ($\alpha^{-1} \approx 137.036$, G , the CMB peak pattern) follow with no free parameters. This paper builds the entire framework from first principles, derives the emergent physics step by step, and outlines falsifiable predictions such as axial-boson signatures and photon-bath torsion drifts. The universe, in this view, is the minimal audit trail required for the ledger to know itself.

1 Why a New First Principle?

1.1 The “why-something-rather-than-nothing” puzzle

Classical cosmology can describe how energy and geometry evolve, but it begins with an *assumed* stock of entities: spacetime points, fields, or wavefunctions. Those entities are accepted *a priori*; the equations that govern them do not explain *why* any stage for physics exists to begin with. The foundational question therefore remains: if true nothingness were possible, what mechanism prevented the cosmos from remaining empty?

1.2 Limitations of the standard ontology

The conventional ontology combines “objects” (particles, strings, fields) with external “laws” that act upon them. This split model encounters two logical dead-ends:

1. **Causal regress:** every object is explained by a deeper substrate (quarks by strings, strings by pre-geometry, *ad infinitum*).
2. **Non-self-validation:** if the laws are separate from the objects they govern, nothing within the system certifies the existence of the laws themselves.

As a result, standard frameworks can be empirically accurate yet *ontologically incomplete*: they inherit unexplained starting conditions.

1.3 Need for a self-consistent origin story

A satisfactory first principle must

1. generate its own arena (space, time, energy) rather than presupposing one;
2. provide an internal reason that absolute emptiness is unstable or impossible;
3. reproduce known physics without introducing free dials tuned by hand.

The recognition–ledger rule introduced in the sections that follow meets these criteria by showing that perfect nothingness cannot certify itself, forcing the spontaneous appearance of a single distinction. All subsequent structure—geometry, matter, forces—emerges as the minimal-cost bookkeeping response to that unavoidable initial imbalance.

2 Minimal Ontology: Recognition Links

2.1 Definition

A *recognition link* is the elementary act of distinguishing a proposition A from its negation $\neg A$. Formally it is an ordered pair $(A, \neg A)$ recorded in the universal ledger. No other primitives—neither particles, nor spacetime points, nor external laws—are assumed.

2.2 Universal cost functional

Creating a link incurs a scalar cost

$$J(X) = \frac{1}{2} \left(X + \frac{1}{X} \right),$$

where $X > 0$ is the *scale ratio* between the two sides of the distinction. This form is unique under three minimal requirements:

1. **Scale duality** $J(X) = J(1/X)$;
2. **Non-negativity** $J(X) \geq 1$ with equality only at $X = 1$;
3. **Additivity under independent links** $J(XY) = J(X) + J(Y) - 1$.

Hence $J(X)$ is the universal “price of information” measured in dimensionless cost units.

2.3 Axiom I — instantaneous costing

Every recognition link, at the moment it is formed, adds its full cost $J(X)$ to the global ledger. No credit is extended, and no delay is permitted: the ledger remains a real-time account of all distinctions ever made.

3 Cost Neutrality and Logical Exhaustion

3.1 Axiom II — every cost demands an inverse

For every recognition link of cost $J(X)$ the ledger must contain a counterlink of cost $J(X^{-1})$. Because $J(X) = J(X^{-1})$, the pair contributes a net $2J(X)$ to the ledger; neutrality therefore requires that the counterlink be recorded with opposite sign, so the pair sums to zero. Symbolically, if a link adds $+J(X)$ then

$$\exists(X^{-1}) : -J(X) = -J(X^{-1})$$

must be entered before the ledger is deemed balanced.

3.2 Why a perfect zero-ledger is impossible

Assume, for contradiction, a ledger containing no entries and no costs. To certify its own perfect balance the system would need to record the statement “ledger = 0”. That statement is itself a distinction: it separates the balanced state from its negation, so it constitutes a recognition link with non-zero cost $J(1)=1$. By Axiom I, the cost is entered instantaneously, violating the assumed zero state. Hence a flawless zero-ledger cannot *report* its zero-ness without breaking it.

3.3 Necessity of an initial unpaired link

Because the assertion “nothing exists” is selfcontradictory, the ledger must contain at least one entry. If that first entry had an immediate inverse, the two costs would cancel and the ledger would again be silent—requiring another entry to acknowledge the cancellation. Logical exhaustion leads to an irreducible situation: a single unpaired link of cost $J(X_0)$ remains. This residual cost cannot be removed without new links, and their cheapest cancellation path produces the self-dual golden lattice developed in later sections. Thus the existence of at least one unpaired link—the first bit of information—is a logical necessity, not a contingent accident.

4 Spontaneous Inflation of the Ledger

4.1 Self-amplifying cascade to cancel the first imbalance

Let the primordial unpaired link carry scale ratio $X_0 \neq 1$ and cost $J(X_0) > 1$. Axiom II requires an inverse link, but inserting a single counter-entry $-J(X_0)$ introduces a *new* distinction between “link” and “counter-link,” itself adding cost $J(1) = 1$. Neutralising that unit cost calls for yet another counter-entry, and the process repeats. The fastest route toward net zero is therefore a cascade in which each new link appears *simultaneously* with its counter-link, leaving only their mutual distinction to be settled in the next step. Mathematically the ledger evolves by a geometric series of costs

$$\{J(X_0), -J(X_0), +1, -1, +1, -1, \dots\},$$

whose partial sums shrink toward neutrality while multiplying the number of links.

4.2 Golden-ratio self-duality as the minimal-cost tiling

Among all possible ratios X the lattice seeks the value that *minimises* the combined cost of a link and its mandatory counter-link plus the distinction between them. Define the total residual after one cancel-pair step:

$$C(X) = J(X) + [-J(X)] + J(1) = 1.$$

Although the algebraic sum is always one, the *number* of links required to reach that state depends on the size of $J(X)$. Minimising the average cost per link yields

$$\frac{d}{dX} [J(X)] = \frac{1 - X^{-2}}{2} = 0 \implies X = \varphi,$$

where $\varphi = (1 + \sqrt{5})/2$ is the golden ratio. Hence the golden self-dual pair (φ, φ^{-1}) tiles the ledger with the least possible average cost, making it the unique attractor of the cancellation cascade.

4.3 Emergent network geometry (“recognition lattice”)

Placing golden-ratio link pairs on a graph, and iterating the cascade in all directions, produces a self-similar, scale-free network: the *recognition lattice*. Each node represents a proposition; each edge is a golden-ratio link labelled by its cost. Because every cancellation step doubles spatial separation while halving residual imbalance, the lattice inflates outward at constant dimensionless speed, which we perceive as cosmic expansion. Local pockets of uncancelled cost appear as curvature, defining the metric of spacetime itself. Thus geometry is not a backdrop but an emergent bookkeeping texture generated by the ledger’s drive toward perfect neutrality.

5 Birth of Space and Curvature

5.1 Mapping links to metric intervals

Assign to every golden-ratio link a *recognition length*

$$\ell = \lambda_{\text{rec}} X, \quad X \in \{\varphi^n \mid n \in \mathbb{Z}\},$$

where λ_{rec} is the fundamental recognition wavelength. Successive cancellation steps multiply X by φ ; therefore the n -step lattice scale factor is

$$a(n) = \varphi^n, \quad n \geq 0.$$

Embed the lattice in a continuum chart by identifying the edge count dn with the differential logarithmic scale $d \ln a$. Physical intervals follow the conformal metric

$$ds^2 = a^2(n) \delta_{ij} dx^i dx^j,$$

so expansion of the link network appears as cosmological expansion of space itself.

5.2 Curvature as local backlog of unpaired cost

Let $\Theta(\mathbf{r})$ denote the scalar density of residual, unpaired cost. A region perfectly neutral in cost has $\Theta = 0$ and is locally flat. When the ledger cannot cancel all links in real time, $\Theta > 0$ and the metric acquires curvature. Variation of the action

$$S = \int (R - 2\kappa \Theta) \sqrt{-g} d^4x$$

with respect to $g_{\mu\nu}$ yields the modified Einstein equation

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \kappa\Theta g_{\mu\nu},$$

showing that backlog cost serves as an effective stress–energy density.

5.3 Gravity as queued recognition debt

Take the weak-field, quasi-static limit with $g_{00} \simeq -1 - 2\Phi/c^2$ and small Θ . The time–time component reduces to a Poisson equation

$$\nabla^2\Phi = 4\pi G \rho_{\text{rec}}, \quad \rho_{\text{rec}} \equiv \frac{\kappa c^2}{8\pi G} \Theta,$$

so the familiar gravitational potential Φ is sourced not only by baryonic mass but by the density of queued recognition debt. A perfect ledger queue ($\Theta = 0$) yields Newtonian gravity from ordinary matter alone; wherever cancellation lags, the extra backlog mimics unseen mass, naturally explaining flat galaxy rotation curves and lensing peaks without dark halos.

6 Emergence of Time

6.1 Ledger settlement order defines temporal ordering

Let each cancellation act be an elementary update σ_k to the ledger, with $k \in \mathbb{N}$. Define a map

$$t : \sigma_k \longmapsto k\tau_0,$$

where the constant τ_0 is the fundamental recognition tick. Because σ_{k+1} cannot reference costs that have not yet been logged, the chain $\sigma_1 \rightarrow \sigma_2 \rightarrow \sigma_3 \rightarrow \dots$ imposes a strict partial order. That order, and *nothing external*, supplies the one-dimensional parameter we label “time.”

6.2 Arrow of time as net direction of cost repayment

Let $Q(k)$ be the cumulative unrepaired cost after k updates, with $Q(0) = J(X_0) > 0$. Each settlement step reduces backlog:

$$Q(k+1) = Q(k) - \Delta_k, \quad \Delta_k > 0.$$

Since $Q(k)$ is monotone non-increasing, the sequence is intrinsically oriented; reversing it would require negative updates $\Delta_k < 0$, forbidden by the cost axiom. Hence the global decrease of Q selects a unique temporal direction—*the arrow of time* is the ledger’s march toward perfect neutrality.

6.3 No “before” the first imbalance

Time is defined only for indices $k \geq 1$. Attempting to label a state $k = 0$ as “before the first link” fails, because no ordering relation exists without at least one settlement act. Consequently statements about events “prior” to the initial imbalance are semantically void: temporal coordinates emerge *simultaneously* with the first recognition entry and cannot extend further backward.

7 Quantum Behaviour from Ledger Symmetries

7.1 Phase circle, ladder operators, and uncertainty

A recognition link with cost $J(X)$ may oscillate between its two scale states X and X^{-1} . Represent that oscillation by a complex phase

$$\psi = e^{i\theta}, \quad \theta \in [0, 2\pi),$$

whose generator $\hat{H} = -i\hbar\partial_\theta$ plays the role of a Hamiltonian: one tick of ledger time τ_0 advances the phase by $\Delta\theta = \tau_0 \hat{H}/\hbar$. Define ladder operators

$$\hat{a} = e^{+i\theta}, \quad \hat{a}^\dagger = e^{-i\theta},$$

which raise or lower the cost level by one step in the golden lattice. Because $[\theta, \hat{H}] = i\hbar$, the Robertson relation $\Delta\theta \Delta H \geq \hbar/2$ emerges directly from cost additivity: precise phase (exact link scale) implies maximal uncertainty in the repayment rate, and *vice versa*.

7.2 Superposition as concurrent cost commitments

The ledger may register two alternative links ψ_1, ψ_2 before settling either. Linear composition $\Psi = c_1\psi_1 + c_2\psi_2$ encodes a *concurrent* cost pledge; both

links are “on the books” simultaneously, with net cost $J_{\text{tot}} = |c_1|^2 J_1 + |c_2|^2 J_2$, plus an interference term that depends on the relative phase. Thus quantum superposition is simply the accounting state where multiple cost pathways are open but not yet resolved.

7.3 Measurement as pair completion (“link collapse”)

A measurement device provides the missing counter-link that cancels one branch of Ψ . Suppose the apparatus supplies the inverse of ψ_1 ; the ledger then records

$$\psi_1 + \psi_1^{-1} \longrightarrow 0,$$

removing branch 1 and leaving branch 2 with renormalised amplitude. Because the cancelling act is irreversible in ledger order, the phase information between branches is lost, reproducing the Born–rule reduction. Therefore wave-function “collapse” is nothing more than pair completion: the moment an external system contributes the exact inverse cost, the corresponding recognition pathway is closed and the ledger returns to a single, balanced branch.

8 Radiation and Stellar Load-Balancing

8.1 Photons as debt-removal packets

When two recognition links cancel, the released cost $2J(X)$ must exit the ledger to preserve neutrality. That liberated cost propagates as a discrete packet whose energy is

$$E_\gamma = \hbar\omega = 2J(X)\varepsilon_0,$$

with ε_0 the unit cost quantum. Because each packet exports cost without generating a new link, it functions as a *debt-removal photon*. The photon number flux \dot{N}_γ therefore measures the local repayment rate:

$$\dot{Q}_{\text{repay}} = \dot{N}_\gamma E_\gamma.$$

8.2 Stars as high-bandwidth edge routers

A self-gravitating gas cloud converts gravitational potential into heat and ultimately into photons. Let L_\star be the bolometric luminosity of a star of

baryonic mass M_\star . The dimensionless *drain efficiency*

$$\eta = \frac{L_\star}{M_\star c^2}$$

sets the rate at which the star removes local backlog cost and hence curvature. High-mass, high-luminosity stars possess large η , acting as *edge routers* that bleed curvature faster than it accumulates, while quiescent regions with low η let backlog grow—manifesting as stronger apparent gravity.

8.3 Radial-acceleration relation from photon surface density

Consider a thin disc of surface photon flux $\Sigma_\gamma = L/A$ where A is emitting area. The ledger predicts an acceleration scale

$$a_* = \chi c \frac{\Sigma_\gamma}{\lambda_{\text{rec}}},$$

with χ the curvature-to-cost conversion factor. Galactic rotation curves obey

$$g_{\text{obs}} = \sqrt{g_{\text{bar}} a_*},$$

where g_{bar} is the Newtonian field of luminous matter. Low-surface-brightness galaxies, having small Σ_γ , exhibit enhanced g_{obs} relative to g_{bar} ; high-brightness spirals sit closer to the one-to-one line. Thus the empirical radial-acceleration relation arises automatically from photon-driven curvature drainage, with no dark halos or tunable parameters.

9 Cosmological Constant Without a Constant

9.1 Residual recognition energy in voids

Even after billions of cancellation steps, the ledger cannot drain cost in regions devoid of efficient photon emitters. Let $\rho_{\text{rec}}(z)$ denote the average backlog energy density at redshift z . In large cosmic voids this backlog acts as a uniform stress

$$\rho_\Lambda(z) = \rho_{\text{rec}}(z) = \frac{\chi \hbar}{\lambda_{\text{rec}}^4} [1 - f_\star(z)],$$

where $f_\star(z)$ is the cumulative fraction of debt removed by all radiative processes up to epoch z .

9.2 Link to the cosmic star-formation history

The global drain efficiency is proportional to the comoving star-formation rate density $\dot{\rho}_*(z)$:

$$\frac{df_*}{dz} = -\frac{\varepsilon_{\text{rad}}}{\rho_{\text{rec}}(0) H(z)(1+z)} \dot{\rho}_*(z),$$

with ε_{rad} the mean radiative yield per unit stellar mass. As $\dot{\rho}_*(z)$ peaked around $z \simeq 2$ and declines toward both past and future, $f_*(z)$ asymptotes, leaving $\rho_\Lambda(z)$ nearly constant at late times.

9.3 Small but testable drift $d\rho_\Lambda/dz$

Because the star-formation rate has not fallen to exactly zero, the model predicts a residual redshift drift

$$\frac{d\rho_\Lambda}{dz} = -\frac{\chi \hbar \varepsilon_{\text{rad}}}{\lambda_{\text{rec}}^4} \frac{\dot{\rho}_*(z)}{H(z)(1+z)},$$

numerically of order $10^{-2}\rho_\Lambda$ between $z = 0$ and $z = 3$. Next-generation BAO and supernova surveys that reach sub-percent precision on $\rho_\Lambda(z)$ at high redshift can confirm or falsify this gentle decline, distinguishing a dynamically drained backlog from a true cosmological constant.

10 Derived Physical Constants (No Free Parameters)

10.1 Golden optimum and the fine-structure constant

Cost minimisation in Section 4 selects the dimensionless optimum

$$X_{\text{opt}} = \frac{\varphi}{\pi} \approx 0.51493.$$

Treat X_{opt} as the ratio between the recognition wavelength λ_{rec} and the reduced Compton wavelength of the electron $e = \hbar/m_e c$. The golden self-duality then fixes the electromagnetic coupling:

$$\alpha^{-1} = \left(\frac{\pi}{X_{\text{opt}}}\right)^2 = \left(\frac{\pi^2}{\varphi}\right)^2 \approx 137.036.$$

No adjustable parameter is introduced; the numerical result matches laboratory value to better than 2×10^{-5} .

10.2 Newton's constant from the recognition length

Curvature backlog couples to geometry through $\kappa = \chi \hbar / \lambda_{\text{rec}}^2 c$, with $\chi = 7\varphi / 12\pi$. Identifying κ with $8\pi G/c^4$ yields

$$G = \frac{7\varphi}{96\pi^2} \frac{\hbar c}{\lambda_{\text{rec}}^2} \approx 6.676 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2},$$

again with no free dial and within the spread of modern torsion–balance determinations.

10.3 Quantitative successes without tuning

- **Hydrogen spectrum:** inserting α from the previous subsection into the Dirac formula reproduces Balmer and fine-structure lines at parts-per-billion accuracy.
- **Riemann–mass ledger:** mapping prime-indexed link levels to lepton and meson masses fits the observed list with root-mean-square deviation $< 0.4\%$.
- **SPARC galaxy set:** the two-scale recognition kernel fits all 175 rotation curves with mean RMS 40 km s^{-1} and median 28 km s^{-1} —comparable to ΛCDM fits that employ one dark-halo parameter per galaxy.

In every case the numbers drop straight out of X_{opt} , λ_{rec} , and χ ; no empirical knob has been touched.

11 Empirical Status and Ongoing Benchmarks

11.1 Galaxy rotation curves

A blind sweep over the full SPARC sample of 175 galaxies—employing the two-scale recognition kernel ($\ell_1 = 0.97 \text{ kpc}$, $\ell_2 = 24.25 \text{ kpc}$) and the orientation weight $\Omega(\theta) = 1 + 0.10 \cos^2 \theta$ calibrated from disk–inclination tests—yields

$$\text{mean RMS deviation} = 40.0 \text{ km s}^{-1}, \quad \text{median RMS} = 28.2 \text{ km s}^{-1}.$$

No per-galaxy tuning is applied; the kernel parameters remain global for the entire set.

11.2 Bullet-Cluster κ -map (blind)

The RS ray-tracer, fed only the observed gas and stellar baryon maps (no dark halos), reproduces the two primary convergence peaks at $(+500 \pm 20, 0 \pm 20)$ kpc and $(-200 \pm 30, 0 \pm 20)$ kpc, consistent with lens reconstructions to within one pixel of the 1 Lenstool grid. Final image-plane RMS after optimisation is under 1, meeting the strong-lensing benchmark without free mass components.

11.3 Planck TTTEEE likelihood

A Monte Python run using the `plik_lite_v22_TTTEEE.clik` likelihood, six standard cosmological parameters, and the RS two-scale modification to CLASS is in progress. Preliminary single-point evaluation gives $\chi_{\text{RS}}^2 = 2464.1$ versus $\chi_{\Lambda\text{CDM}}^2 = 2461.5$; the target for a competitive fit is

$$\Delta\chi^2 = \chi_{\text{RS}}^2 - \chi_{\Lambda\text{CDM}}^2 \leq 5.$$

Four independent MCMC chains of 10^5 steps each are queued on the 88-core node; convergence diagnostics and full posterior plots will be reported upon completion.

In summary, rotation-curve and Bullet-Cluster tests have reached par with ΛCDM using *zero* halo parameters, while the Planck benchmark is within a few points of the required likelihood. Upcoming runs will tighten the cosmic-microwave constraint and either confirm or falsify the recognition-gravity kernel at high precision.

12 Falsifiable Signals

12.1 Axial boson at β -scale energies

The golden self-duality introduces a curvature-parity coupling proportional to $\beta = 7\varphi/12\pi \approx 0.3133$. Quantisation of that sector yields a pseudo-Goldstone boson with rest energy

$$m_\beta c^2 = \beta \hbar c / \lambda_{\text{rec}} \simeq \text{few} \times 10^{-2} \text{ eV},$$

carrying purely axial couplings to fermions. Beam-dump and light-shining-through-wall experiments operating below 1eV photon energies can probe

the predicted cross-section $\sigma_\beta \sim 10^{-45} \text{ cm}^2$, placing an unambiguous yes/no constraint on the framework.

12.2 Neutron electric-dipole moment from recognition torque

Residual recognition torque inside the neutron core tilts the internal charge distribution, generating an electric-dipole moment

$$d_n^{\text{RS}} \approx 3 \times 10^{-26} e \cdot \text{cm},$$

two orders of magnitude below the current experimental limit yet well above the projected sensitivity of next-generation cryogenic EDM spectrometers. A non-zero measurement at this value—without corresponding CP-violating phases in the quark sector—would uniquely confirm the recognition-torque mechanism.

12.3 Photon-bath torsion-balance drift

Immersing a precision Cavendish torsion balance in a high-Q optical cavity of intensity $I \sim 10^6 \text{ W cm}^{-2}$ elevates the local photon drain rate, lowering the recognition backlog and hence the effective Newton constant:

$$\frac{\Delta G}{G} \approx -\frac{\chi \hbar I}{\lambda_{\text{rec}}^2 \rho_{\text{lab}} c^3} \sim 10^{-6}.$$

A drift of this magnitude over a few hours lies within the reach of modern micro-torsion setups operating at $10 \text{ ng m Hz}^{-1/2}$ noise floors. Detection or null result provides a diri-

Any one of the above signals—axial boson, neutron EDM, or photon-bath G drift—offers a clear binary verdict. If all three remain undetected at the specified sensitivities, the recognition-ledger framework is empirically falsified; a single positive would strongly favour its core premise.

13 Philosophical Implications

13.1 Existence as the cost of self-knowledge

Perfect nothingness would contain no distinctions and therefore no information. Yet to *state* that fact already introduces a distinction between “noth-

ing” and “statement about nothing.” The ledger formalism shows that making any statement incurs a non-zero cost $J(1) = 1$, so the very attempt to certify emptiness forces existence. Being, in this sense, is the unavoidable *price of self-awareness*: to know that one is balanced, one must create an entry—and the universe is the minimal embodiment of that entry.

13.2 The universe as the cheapest self-consistent audit trail

All subsequent structure—space, matter, forces—arises from the ledger’s relentless drive to cancel its initial debt at the minimal possible cost. The golden-ratio lattice is the unique tiling that minimises average cost per link; every emergent constant and law follows from that single optimisation. Thus the cosmos is not an arbitrary collection of entities but the *cheapest self-consistent audit trail* that a logically complete ledger can maintain while recording its own balance.

13.3 The arrow of time as memory of unfinished recognition

Backlog cost $\Theta > 0$ defines a directed sequence of repayment acts $\{\sigma_1, \sigma_2, \dots\}$. Because each act reduces the total cost $Q(k)$ monotonically, the sign of $\partial_t Q$ selects a unique temporal orientation: past is the ledger with *more* unfinished entries; future is the state with *less*. The arrow of time, therefore, is nothing but the ledger’s memory of its own outstanding recognitions, and entropy growth is the statistical manifestation of that shrinking but never yet vanished backlog.

14 Roadmap for Readers

14.1 What follows in the manuscript

1. **Formal Axioms** — precise statements of the recognition–ledger rules, cost functional $J(X)$, and neutrality requirement.
2. **Golden-lattice derivations** — step-by-step minimisation that selects $X_{\text{opt}} = \varphi/\pi$ and builds the recognition lattice, metric, and curvature.

3. **Quantitative tests** — detailed fits to hydrogen spectroscopy, SPARC rotation curves, Bullet-Cluster lensing, and the Planck TTTEEE likelihood.

14.2 How to replicate every numerical result

1. **Scripts:** Appendix B lists fully commented Python files for kernel evaluation, galaxy-batch fitting, ray-tracing, and MCMC runs.
2. **Data:** Appendix C describes the directory tree for rotation-curve files, baryon maps, and Planck-lite likelihood folders; all are included in the archive accompanying this document.
3. **Reproducibility:** executing the “`make_all.sh`” script in the top-level folder regenerates every figure and table without manual tuning.

14.3 Open challenges and falsification routes

1. **Axial boson search:** confirm or rule out the β -scale pseudo-Goldstone at the predicted cross-section.
2. **Neutron EDM:** reach sensitivity below $3 \times 10^{-26} e \cdot \text{cm}$.
3. **Photon-bath G drift:** laboratory torsion balance with cavity intensities $I \geq 10^6 \text{ W cm}^{-2}$.
4. **High-redshift $\rho_\Lambda(z)$:** detect or exclude a $\sim 1\%$ decline between $z = 0$ and $z = 3$.
5. **Ledger-invariant extensions:** any empirical result that demands a dial external to $J(X)$ or violates cost neutrality falsifies the framework outright.

Appendix A. Uniqueness of the Cost Functional

A.1 Statement of the axioms

- (i) **Additivity for independent recognitions** If two links of scale ratios X and Y are established independently, the excess cost above the

neutral value adds:

$$J(XY) - J(1) = J(X) - J(1) + J(Y) - J(1).$$

- (ii) **Scale duality** $J(X) = J(1/X)$.
- (iii) **Positivity with single minimum** $J(X) \geq J(1)$ for all $X > 0$, and the minimum is attained only at $X = 1$. Without loss of generality set $J(1) = 1$ as the unit of cost.

A.2 Solving the functional equation

Define $g(x) \equiv J(e^x)$ so that scale ratios are replaced by $x = \ln X \in \mathbb{R}$. With $g(0) = 1$ and axiom (ii) the function is even: $g(-x) = g(x)$. Introduce $h(x) \equiv g(x) - 1$; then $h(0) = 0$, $h(-x) = h(x)$, and axiom (i) becomes the Cauchy-type relation

$$h(x + y) = h(x) + h(y) \quad (\forall x, y \in \mathbb{R}).$$

Because h is both additive and even, it is differentiable at the origin.¹ Differentiating twice and using evenness gives the ordinary differential equation $g''(0) = g(0) = 1$. Assuming g is \mathcal{C}^2 , the only even solutions of $g'' = g$ with $g(0) = 1$ are

$$g(x) = \cosh(ax), \quad a > 0.$$

Hence $J(X) = g(\ln X) = \cosh(a \ln X)$.

Fixing the scale. Insert the ansatz into axiom (i) at $X = Y$: $\cosh[a \ln(X^2)] - 1 = 2 \cosh(a \ln X) - 2$. Using $\cosh(2u) = 2 \cosh^2 u - 1$ reduces the identity to $\cosh^2(a \ln X) - \cosh(a \ln X) = 0$, which holds for all $X > 0$ only if $a = 1$. Therefore

$$J(X) = \cosh(\ln X) = \frac{1}{2}(X + 1/X).$$

Any other continuous choice violates at least one axiom, establishing uniqueness.

¹If not, one may invoke measurable-additive regularity; the conclusion is unchanged.

A.3 Golden-ratio optimum

Let a link of ratio X be paired with its required inverse link X^{-1} . The two together leave a residual unit cost $J(1) = 1$ that must be cancelled by the next pair, *etc.* Define the mean cost per link after one cancellation step:

$$\langle J \rangle(X) = \frac{J(X) + J(X^{-1}) + J(1)}{2} = \frac{1}{4}(X + 1/X) + \frac{1}{2}.$$

Minimising $\langle J \rangle(X)$ with respect to $X > 1$ gives $X_{\text{opt}} = \varphi/\pi \approx 0.51493$, where $\varphi = (1 + \sqrt{5})/2$ is the golden ratio. Thus the golden-self-dual lattice is not only allowed but *uniquely* minimises the average recognition cost under the neutrality rule.