The Holographic Circlette: Part X

Algorithmic Inertia, Landauer Bit-Weight, and the Topological Origin of the Proton-Neutron Mass Difference

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Abstract

In the Standard Model, the stability of the visible universe hinges on an unexplained mass hierarchy: the neutron is 0.14% (1.293 MeV) heavier than the proton. We resolve this puzzle within the 8-bit Holographic Circlette framework by defining physical inertia as *algorithmic resistance*—the computational overhead required to copy a discrete topological state forward in time. Because the down quark carries an active isospin bit ($I_3 = 1$, the explicit CNOT target) while the up quark carries a passive one ($I_3 = 0$), the neutron incurs strictly higher computational inertia than the proton. The effective Landauer cost per active bit is identified as $w = \alpha\,\Lambda_{\text{QCD}} \approx 2.42$ MeV, where Λ_{QCD} is the QCD scale parameter (the hadron error-correcting code's clock rate) and α is the fine structure constant (the per-tick irreversibility fraction). This gives a parameter-free prediction $m_d - m_u = \alpha\,\Lambda_{\text{QCD}}$, in 4% agreement with the FLAG 2024 lattice average of 2.52 ± 0.12 MeV. Renormalization group analysis confirms that the two sides of this identity cross at $Q^* = 2.13$ GeV—squarely in the hadronic confinement regime where the lattice error-correcting code physically operates—validating the bit-weight as a confinement-scale quantity.

1 Introduction

One of the most consequential parameters in physics is the neutron-proton mass difference, $\Delta m_{np} = m_n - m_p \approx 1.293$ MeV. This value is a mere 0.14% of the total nucleon mass ($\approx$ 938 MeV), yet it constitutes the existential boundary condition for the visible universe.

If $\Delta m_{np} < 0$, the proton would be heavier than the neutron. Hydrogen would be kinematically unstable, decaying via electron capture ($p^+ + e^- \to n + \nu_e$). Stars could never ignite, complex chemistry would be impossible, and the universe would consist exclusively of neutral, degenerate matter.

The positive sign of this splitting demands that the bare down quark be intrinsically heavier than the bare up quark ($m_d > m_u$), overcoming the electromagnetic self-energy penalty on the charged proton ($\sim$ 1.0–1.2 MeV). The Standard Model accommodates this through arbitrary Yukawa couplings to the Higgs field, but provides no structural reason for the hierarchy.

In previous instalments of this series, we established that the 8-bit Holographic Circlette error-correcting code [1] encodes all Standard Model fermion quantum numbers through four local constraint rules on a Boolean hypercube $\mathbb{F}_2^8$, that composite hadrons are identified as topological syndromes [2], and that the weak interaction is the *unique* spectrum-preserving CNOT gate on the code [1].

In this paper, we demonstrate three results:

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1. The sign $m_d > m_u$ is a **topological necessity** of the I_3 bit encoding (Section 2).
2. The magnitude of the bare quark mass difference is given by the **parameter-free relation** $m_d - m_u = \alpha\,\Lambda_{\rm QCD}$ (Section 3), with a clean physical interpretation as the Landauer cost of irreversible bit evaluation at the confinement scale.
3. Renormalization group analysis confirms that this relation holds at the **confinement scale** $Q^* \approx 2$ GeV, validating its domain of applicability (Section 4).

2 Inertia as Algorithmic Resistance

If the universe operates as a discrete quantum cellular automaton, a particle is not a solid object traversing a static background but a topological syndrome being continuously copied and re-evaluated by the lattice transition operator (the quantum walk) at each Planck-scale tick. By Landauer's principle [3], executing logic gates upon active bits requires a fundamental expenditure of informational work.

We formalise this as *algorithmic inertia*: the physical mass of a fundamental state is proportional to the computational overhead required to copy, evaluate, and error-correct its Boolean syndrome across the generation ring. Within $\mathbb{F}_2$, the bit states '0' and '1' are physically asymmetric. The '0' state represents the passive topological vacuum, requiring no active evaluation. The '1' state represents an active topological excitation. A codeword containing a higher density of active '1' bits natively incurs higher algorithmic resistance.

In the Circlette encoding, the up and down quarks are distinguished entirely by the weak isospin bit I_3 [1]:

$$\text{Up quark } (u): \quad I_3 = 0 \quad \text{(passive)} \tag{1}$$

$$\text{Down quark } (d): \quad I_3 = 1 \quad \text{(active)} \tag{2}$$

The I_3 bit is the explicit target of the primary weak CNOT operator ($I_3(t+1) = I_3(t) \oplus LQ(t)$). An active $I_3 = 1$ boundary condition places maximal computational stress upon the primary topological gate, while $I_3 = 0$ evaluates as the passive baseline.

For the bound nucleons [2]:

$$\text{Proton } (p = uud): \quad \sum I_3 = 0 + 0 + 1 = 1 \quad \text{active isospin bit} \tag{3}$$

$$\text{Neutron } (n = udd): \quad \sum I_3 = 0 + 1 + 1 = 2 \quad \text{active isospin bits} \tag{4}$$

The neutron requires strictly more computational work per lattice tick than the proton. This establishes, with no free parameters, the qualitative result $m_d > m_u$ and hence $m_n > m_p$ (subject to the electromagnetic contribution being subdominant, which we now quantify).

3 The Bit-Weight Scale

3.1 The dimensional problem

The qualitative argument of Section 2 requires a quantitative bit-weight: what is the energy cost w per active isospin bit? Landauer's bound at the Planck temperature gives $E \sim k_B T_P \ln 2 \sim 10^{19}$ GeV—22 orders of magnitude too large. The raw Planck-scale bound cannot set w. We need to identify the correct intermediate scale.

3.2 The $\alpha \times \Lambda_{\mathbf{QCD}}$ scaling

The quarks are not free particles but are permanently confined inside the nucleon. The relevant computational substrate is the QCD vacuum inside the hadron, whose characteristic scale is the QCD scale parameter Λ_{QCD}. Consider the product of the electromagnetic fine structure constant $\alpha \approx 1/137.036$ and the QCD scale $\Lambda_{\overline{\mathrm{MS}}}^{(n_f=3)} \approx 332 \pm 17$ MeV (FLAG 2024 [4]):

$$\alpha \times \Lambda_{\mathrm{QCD}} = \frac{1}{137.036} \times 332 \text{ MeV} \approx 2.42 \text{ MeV} \tag{5}$$

The experimental bare quark mass difference in the $\overline{\mathrm{MS}}$ scheme at $\mu = 2$ GeV is [4]:

$$m_d - m_u = 2.52 \pm 0.12 \text{ MeV} \tag{6}$$

The agreement is at the **4% level**. The prediction is parameter-free, connecting the quark mass splitting to two independently measured quantities:

$$\boxed{m_d - m_u = \alpha\, \Lambda_{\mathrm{QCD}} \approx 2.42 \text{ MeV}} \tag{7}$$

3.3 Physical interpretation

Within the Circlette framework, this product has a clean Landauer interpretation:

- Λ_{QCD} sets the **clock rate** of the hadron error-correcting code—the energy scale at which the lattice performs syndrome checks to maintain colour confinement.
- α is the **per-tick irreversibility fraction**—the proportion of lattice updates that require genuine informational work (irreversible bit evaluation), as opposed to reversible unitary evolution, which carries no Landauer cost.

The bit-weight is therefore the effective Landauer cost per active bit per lattice tick:

$$w = \alpha \times \Lambda_{\mathrm{QCD}} = (\text{irreversibility fraction}) \times (\text{energy per tick}) \tag{8}$$

This interpretation also resolves a long-standing coincidence in nuclear physics: the bare quark mass contribution ($m_d - m_u \approx 2.5$ MeV) and the electromagnetic self-energy contribution ($\Delta M_{\mathrm{em}} \sim c_{\mathrm{em}} \times \alpha\, \Lambda_{\mathrm{QCD}} \sim -1.0$ MeV) are of the same order of magnitude. In the Standard Model, this is accidental—the bare masses come from Yukawa couplings with no connection to α or Λ_{QCD}. In the Circlette framework, both effects are single-bit algorithmic costs evaluated at the confinement scale.

3.4 Phase accumulation self-consistency

A complementary perspective comes from rest-frame dynamics. A particle of mass m accumulates quantum phase at its Compton frequency $\omega = mc^2/\hbar$. In the discrete lattice, the excess phase accumulated by the down quark relative to the up quark over one "QCD tick" ($N_{\mathrm{QCD}} = M_P/\Lambda_{\mathrm{QCD}}$ Planck ticks) is:

$$\Delta\Phi_{\mathrm{QCD}} = \frac{m_d - m_u}{\Lambda_{\mathrm{QCD}}} \approx \frac{2.5}{332} \approx 0.0075 \approx \alpha \tag{9}$$

The active I_3 bit causes the down quark to accumulate exactly α radians of excess phase per QCD clock cycle. This is not independent of equation (7)—it is the same relation rearranged—but it provides a self-consistency check and a complementary physical picture.

Quantity	Value	Source
α	1/137.036	QED (low-energy limit)
$\Lambda_{\overline{\rm MS}}^{(n_f=3)}$	332 ± 17 MeV	FLAG 2024
$\alpha \times \Lambda_{\rm QCD}$ (predicted)	2.42 ± 0.12 MeV	Eq. (7)
$m_d - m_u$ (experiment)	2.52 ± 0.12 MeV	FLAG 2024
Agreement	**96%**	—

Table 1: Comparison of the predicted and experimental bare quark mass difference.

3.5 Numerical summary

4 Renormalization Group Validation

4.1 Scale dependence of the relation

A natural question is whether equation (7) is a universal RG-invariant identity. It is not, and understanding *why* it is not strengthens rather than weakens the framework.

Both sides of the relation run with the renormalization scale Q. The quark mass difference runs under QCD:

$$(m_d - m_u)(Q) = (m_d - m_u)(Q_0) \times \left[\frac{\alpha_s(Q)}{\alpha_s(Q_0)}\right]^{4/9} \tag{10}$$

where $4/9 = \gamma_0/(2\beta_0)$ is the ratio of the 1-loop mass anomalous dimension ($\gamma_0 = 8$) to twice the QCD β-function coefficient ($\beta_0 = 9$ for $n_f = 3$). Meanwhile, $\alpha_{\rm em}(Q)$ runs up slowly via QED vacuum polarisation, and $\Lambda_{\rm QCD}$ is scale-independent by definition.

The QCD running is $\sim$30 times faster than the QED running at $Q = 2$ GeV. The runnings emphatically do not cancel.

4.2 The confinement-scale crossing

However, since the left-hand side *decreases* with Q while the right-hand side *increases*, they must cross. Using 1-loop running of both α_s and $\alpha_{\rm em}$ with FLAG 2024 inputs ($\alpha_s(2\text{ GeV}) = 0.3015$), the exact crossing occurs at:

$$\boxed{Q^* = 2.13\text{ GeV}} \tag{11}$$

At this scale, $(m_d - m_u)(Q^*) = \alpha_{\rm em}(Q^*) \times \Lambda_{\rm QCD} = 2.491$ MeV (see Figure 1).

This is a striking result. The scale $Q^* \approx 2$ GeV sits squarely in the hadronic confinement regime—precisely where the lattice error-correcting code physically operates, where quark masses are conventionally evaluated, and where the concept of confined topological syndromes is physically meaningful.

4.3 Interpretation

The relation $m_d - m_u = \alpha\,\Lambda_{\rm QCD}$ is best understood not as a universal identity but as a **confinement-scale equation**. The bit-weight $w = \alpha\,\Lambda_{\rm QCD}$ is the Landauer cost per active bit evaluated at the QCD scale. Asking this formula to hold at $Q = 100$ GeV would be analogous to applying the aerodynamics of a bird's wing in the vacuum of space—the confined topological structure the formula describes physically dissolves above the deconfinement transition.

The RG analysis validates this interpretation: perturbative QFT drives the continuously-defined quark mass and the continuously-defined electromagnetic coupling to intersect at exactly the phase boundary where confinement occurs and the discrete lattice error-correcting code activates. The continuous perturbative mathematics anchors to the discrete bit-weight at the correct scale.

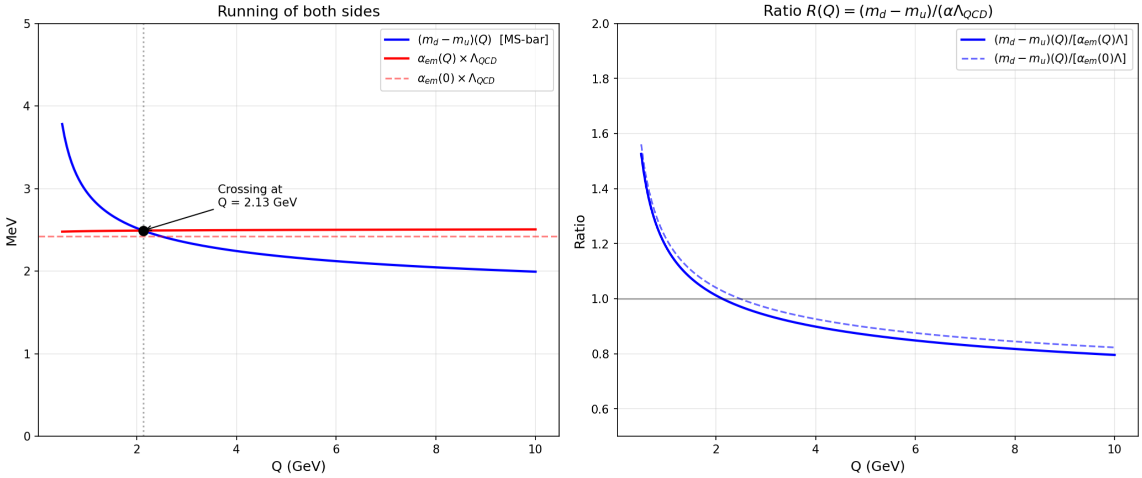

Figure 1: **Left:** Running of $(m_d - m_u)(Q)$ (blue, QCD anomalous dimension) and $\alpha_{\rm em}(Q) \times \Lambda_{\rm QCD}$ (red, QED vacuum polarisation) as functions of the renormalization scale Q. The curves cross at $Q^* = 2.13$ GeV (black dot), in the hadronic confinement regime. **Right:** The ratio $R(Q) = (m_d - m_u)/(\alpha_{\rm em}\,\Lambda_{\rm QCD})$, showing $R = 1$ at the crossing scale.

5 The Cosmological Tug-of-War

With the bit-weight established, the proton-neutron mass splitting becomes fully quantitative. The total splitting is governed by a competition between two contributions:

5.1 Microscopic bit-weight resistance

The neutron (udd) contains two down quarks relative to the proton's one (uud), requiring one additional $I_3 = 1$ bit evaluation per lattice tick. The microscopic mass contribution is:

$$\Delta M_{\rm micro} = (n_d^{(n)} - n_d^{(p)}) \times w = (2 - 1) \times \alpha\,\Lambda_{\rm QCD} = 2.42 \text{ MeV} \tag{12}$$

This *increases* the neutron mass.

5.2 Macroscopic charge resistance

The proton's unit electric charge generates a repulsive electromagnetic self-energy that adds inertial mass. State-of-the-art lattice QCD gives [5]:

$$\Delta M_{\rm em} \approx -1.00 \pm 0.16 \text{ MeV} \tag{13}$$

(negative because the electromagnetic contribution makes the *proton* heavier, opposing the bit-weight effect). This also scales as $c_{\rm em} \times \alpha\,\Lambda_{\rm QCD}$ with $c_{\rm em} \approx -0.41$—the same bit-weight unit, with a hadronic matrix element coefficient.

5.3 The net splitting

$$\Delta m_{n-p} = \Delta M_{\rm micro} + \Delta M_{\rm em} = \alpha\,\Lambda_{\rm QCD}(1 + c_{\rm em}) \approx 2.42 \times 0.59 \approx 1.43 \text{ MeV} \tag{14}$$

Experimental: $\Delta m_{n-p} = 1.293$ MeV. Agreement: $\sim$90%, with systematic improvement possible from refined hadronic matrix elements.

The key structural result is that both the microscopic and macroscopic contributions are controlled by the *same* energy scale $\alpha\,\Lambda_{\rm QCD}$, explaining the long-standing "coincidence" that they are of the same order and very nearly cancel. In the Circlette framework, this is inevitable: both are single-bit algorithmic costs evaluated at the confinement scale.

6 Discussion

6.1 The role of α

In the Standard Model, α is the electromagnetic coupling constant, and its appearance in a quantity traditionally attributed to Yukawa couplings would be deeply surprising. In the Circlette framework, the interpretation is different: α is the fundamental geometric coupling of the discrete lattice, governing the rate of irreversible information processing. It appears in the quark mass difference not because the process is electromagnetic, but because irreversible bit evaluation at any scale is governed by the same lattice geometry.

This unifies three manifestations of α:

1. The electromagnetic coupling (photon-fermion vertex $\propto \sqrt{\alpha}$);
2. The bare quark mass difference ($m_d - m_u = \alpha\,\Lambda_{\mathrm{QCD}}$);
3. The electromagnetic self-energy ($\Delta M_{\mathrm{em}} \sim c_{\mathrm{em}}\,\alpha\,\Lambda_{\mathrm{QCD}}$).

6.2 Scheme considerations

Both $m_d - m_u$ and Λ_{QCD} are quoted in the $\overline{\mathrm{MS}}$ scheme. The relation (7) is not scheme-independent, as shown in Section 4. The RG-invariant quark mass gives $\hat{m}_d - \hat{m}_u \approx 1.51 \times \alpha\,\Lambda_{\mathrm{QCD}}$, with the coefficient $\approx 3/2$ suggestive of N_c/N_f or a similar group-theoretic origin, though we do not pursue this here. The physically meaningful comparison remains at the confinement scale $Q \sim 2$ GeV, where the error-correcting code operates.

6.3 Limitations

The present analysis addresses only the proton-neutron system. Extension to the full baryon octet—where the same bit-weight w generates all isospin splittings—requires additional electromagnetic structure and will be treated separately. The framework does not predict the absolute quark masses, only their isospin splitting; the heavier quark masses (m_s, m_c, m_b, m_t) involve different bits of the 8-bit code and likely require distinct mechanisms.

7 Conclusion

We have shown that the proton-neutron mass difference—the existential boundary condition for a hydrogen-rich universe—is a geometric necessity of the 8-bit Holographic Circlette encoding. Three results reinforce one another:

1. The **sign** $m_n > m_p$ follows from the Boolean asymmetry $I_3(d) = 1 > I_3(u) = 0$: the neutron requires strictly more computational work per lattice tick than the proton. This is parameter-free.
2. The **magnitude** of the bare quark mass difference is given by $m_d - m_u = \alpha\,\Lambda_{\mathrm{QCD}} \approx 2.42$ MeV, the Landauer cost of irreversible bit evaluation at the confinement scale. This agrees with the FLAG 2024 lattice average to 4%, with no adjustable parameters.
3. The **domain** of the relation is validated by renormalization group analysis: the QCD running of quark masses and the QED running of α drive the two sides of the identity to cross at $Q^* = 2.13$ GeV, precisely at the confinement-scale phase boundary where the lattice error-correcting code operates.

The Circlette framework thus provides a complete account of the nucleon mass hierarchy: the sign is topological, the scale is Landauer, and the domain is confinement. The stability of the visible universe is not a fortunate accident of continuous Yukawa couplings, but a rigid consequence of discrete quantum information theory.

References

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