

# Anomaly cancellation from a finite error-correcting code: a Standard-Model compression result

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## Abstract

In the Standard Model (SM), gauge anomaly cancellation is one of the quiet consistency miracles: when the quantum theory is computed, the quark and lepton charges must make several triangle-diagram traces vanish exactly. If they did not, the gauge theory would not be a consistent quantum theory. This paper asks whether that cancellation can be compressed into a small discrete rule rather than accepted as a remarkable coincidence of measured charges.

Within the *Holographic Circlette* finite-QEC substrate, the answer is yes, conditional on the substrate axioms. An  $[8, 4, 4]$  binary error-correcting cell, with four Boolean record rules  $R1$ – $R4$ , admits exactly the SM Weyl content. Exact-rational scripts verify that the admitted states cancel all six SM anomaly conditions; that anomaly-freedom is rare among comparable Boolean sector rules (about 0.8%); that  $N_c = 3$  and the colour charge-weight  $1/3$  are forced; and that the colour-blind readout  $Q = T_3 + Y$  is CPT-covariant. The result reduces, at the continuum field-theory end, to the classical Geng–Marshak and Minahan–Ramond–Warner theorem: with a right-handed neutrino, anomaly cancellation fixes the SM hypercharges. The new contribution is upstream: the special fermion content to which that theorem applies is derived from the finite record cell.

The claim is therefore deliberately modest but useful. It is a compression and explanation of known SM structure, not a new empirical prediction and not a proof of the substrate itself. Its honest status is insight into why several facts we already know hang together.

## 1 Introduction

Two facts about the Standard Model invite explanation rather than mere acceptance. First, the electric charges are quantised in the pattern  $\{0, -1, +\frac{2}{3}, -\frac{1}{3}\}$ , with quark charges fractional in units of  $1/3$ . Second, all chiral gauge anomalies cancel. An anomaly, in this context, is not an experimental irregularity. It is a failure of a classical gauge symmetry to survive quantisation. For a chiral gauge theory such as the SM, anomaly cancellation is a consistency requirement: without it the gauge constraints cannot be imposed consistently in the quantum theory [1, 2, 8, 9].

The cancellation is highly structured. It is not enough for quarks to cancel among themselves or leptons to cancel among themselves. The cancellation uses the full interlocking pattern of one generation: quark doublets, lepton doublets, right-handed singlets, fractional hypercharges, and exactly three colours. In the SM these are consistency conditions that the measured charges happen to satisfy; they are not derived from anything deeper.

A classical body of work showed that the second fact almost forces the first: imposing cancellation of the triangle, mixed gravitational and global  $SU(2)$  anomalies on the SM fermion content determines the hypercharges up to normalisation, and *uniquely* once a right-handed

neutrino is included [3, 4]. Anomaly cancellation thus *quantises hypercharge*—provided one is handed the fermion representation content.

This paper asks a sharper, more structural question. Suppose the fermion content itself is not an input but the output of a small discrete rule. Does anomaly cancellation then become a forced property of that rule, or does it remain a coincidence that the rule was fine-tuned to reproduce? We answer this for the Holographic Circlette substrate, a finite-QEC “it from bit” model [6, 11, 12, 10] in which each cell carries an [8, 4, 4] binary code [7] and four Boolean constraints select exactly the SM fermions. We find that anomaly cancellation is forced and non-generic: the constraints land on an anomaly-free content that most comparable alternatives do not, with the colour number, the colour charge-weight, and the chiral content all pinned.

We are deliberately careful about what this does and does not establish (Section 6). It is a compression: a reduction of several independent SM facts to a few Boolean constraints, in the organising spirit of Mendeleev’s table. It is not a new prediction, and the substrate is posited rather than independently confirmed. The result is therefore “periodic-table-grade” only in the structural-organising sense, a distinction we make precise.

## 2 The discrete substrate

The substrate used here is a small finite record cell. The eight binary labels should not be read as eight new continuous fields. They are bookkeeping labels for the local record: which generation slot is being used, whether the state is lepton-like or quark-like, which colour slot is occupied, the weak-isospin label, chirality, and weak charge. The point of the calculation is that a short set of rules on these labels selects the same chiral fermion content that the SM normally writes in representation-theory language.

**Definition 1** (Register). Each cell carries an 8-bit register  $\mathbf{c} = (G_0, G_1, \text{LQ}, C_0, C_1, I_3, \chi, W) \in \mathbb{F}_2^8$ , the eight bits sitting on the eight triangular faces of a  $Q_3$  cell (the 256-dimensional internal Hilbert space is  $(\mathbb{C}^2)^{\otimes 8}$ ). The bit roles are: generation  $(G_0, G_1)$ , lepton/quark LQ, colour  $(C_0, C_1)$ , weak isospin  $I_3$ , chirality  $\chi$ , and weak charge  $W$ . The code is the extended Hamming code [8, 4, 4] [7].

**Definition 2** (Constraints). The admitted codewords satisfy

$$R1 : \neg(G_0 \wedge G_1) \quad (\text{three generations, not four}), \quad (1)$$

$$R2 : W = \chi \quad (\text{chirality locks to weak charge}), \quad (2)$$

$$R3a : \text{LQ} = 0 \Rightarrow (C_0, C_1) = (0, 0) \quad (\text{leptons are colourless}), \quad (3)$$

$$R3b : \text{LQ} = 1 \Rightarrow (C_0, C_1) \neq (0, 0) \quad (\text{quarks occupy one of three colour slots}), \quad (4)$$

$$R4 : \neg(\text{LQ} = 0 \wedge I_3 = 0 \wedge \chi = 1) \quad (\text{no right-handed neutrino in the active set}). \quad (5)$$

The counting is deliberately elementary. Rule  $R1$  leaves three generation values. Rules  $R3a$ – $R3b$  leave four matter/colour choices: one colourless lepton slot and three quark colour slots. The isospin and chirality bits each have two values, while  $W$  is fixed by  $R2$ . Thus  $R1 \wedge R2 \wedge R3$  gives  $3 \times 4 \times 2 \times 2 = 48$  codewords. Rule  $R4$  removes three right-handed-neutrino patterns, one per generation, leaving

$$\#\{\text{admitted}\} = 45 = 15 \text{ Weyl states} \times 3 \text{ generations}, \quad (6)$$

exactly the SM fermion content without  $\nu_R$ . Each codeword is one left- or right-chiral Weyl fermion according to  $\chi \in \{0, 1\}$ .

### 3 Charge, hypercharge and CPT

The next step is to translate the finite labels into the familiar SM charge language. The important point is that colour is a degeneracy of the quark states, not an additive contribution to electric charge. Reading colour as part of  $Q$  breaks the substrate’s charge conjugation test. Reading charge colour-blindly reproduces the SM charge table and makes the CPT action exact on the finite labels.

We take the electric charge to be *colour-blind*,

$$Q = T_3 + Y, \tag{7}$$

with  $T_3 = \frac{1}{2}Z_f$  on  $SU(2)$  doublets ( $\chi = 0$ ) and  $T_3 = 0$  on singlets ( $\chi = 1$ ), where  $Z_f = (-1)^{I_3}$  is the Pauli- $Z$  eigenvalue of the isospin bit, and  $Y$  the hypercharge. The weak generator  $T_3$  is identified with  $I_3$  because  $I_3$  is the unique bit flipped by the weak coin (a  $\chi$ -controlled CNOT); this is a structural fact about the dynamics, not a convention.<sup>1</sup>

**Colour-blindness is required by CPT.** The substrate implements charge conjugation as the bitwise involution  $\bar{\mathbf{c}} = \mathbf{1} \oplus \mathbf{c}$ . Reading the quark charge offset through a colour sum (as in an earlier “one-hot” packaging  $Q = \frac{1}{2}Z_f + \frac{1}{3}\sum_i Z_{c_i} + \frac{1}{2}Z_p$ ) is *not* CPT-covariant: the one-hot colour term takes the same value on a colour and its conjugate (there is no state with  $\sum_i Z_{c_i} > 0$ , i.e. no  $3 \leftrightarrow \bar{3}$ ), so  $Q(\bar{\mathbf{c}}) \neq -Q(\mathbf{c})$ . With (7) colour-blind, CPT acts as  $(T_3, Y, q) \mapsto (-T_3, -Y, -q)$  and gives  $Q \rightarrow -Q$  exactly, on all 45 codewords; the colour charge  $q \in \mathbb{Z}_3$  conjugates as  $q \mapsto -q$  (the  $3 \leftrightarrow \bar{3}$  map). The colour  $\mathbb{Z}_3$  triality required to realise this conjugation and the  $SU(3)$  centre is supplied by an explicit qutrit clock/shift centre operator on the colour sector (it is *not* carried by the two Boolean colour bits as Pauli operators); see Remark 1.

The hypercharges that follow from (7) and the rep assignment are the standard ones,

$$Y \in \left\{ \frac{1}{6}, \frac{2}{3}, -\frac{1}{3}, -\frac{1}{2}, -1 \right\}, \tag{8}$$

reproducing  $Q \in \{0, -1, +\frac{2}{3}, -\frac{1}{3}\}$  (Table 1).

state	$T_3$	$Y$	$Q = T_3 + Y$	$SU(3)$
$\nu_L$	$+\frac{1}{2}$	$-\frac{1}{2}$	0	<b>1</b>
$e_L$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	<b>1</b>
$u_L$	$+\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$	<b>3</b>
$d_L$	$-\frac{1}{2}$	$+\frac{1}{6}$	$-\frac{1}{3}$	<b>3</b>
$u_R$	0	$+\frac{2}{3}$	$+\frac{2}{3}$	<b>3</b>
$d_R$	0	$-\frac{1}{3}$	$-\frac{1}{3}$	<b>3</b>
$e_R$	0	-1	-1	<b>1</b>

Table 1: Charges as  $Q = T_3 + Y$  for one generation. The four electric charges are unchanged from the historical one-hot packaging; only the read-out is now colour-blind and CPT-covariant.

### 4 Anomaly cancellation

This section is the field-theory consistency check. The finite code has already produced a list of candidate chiral fermions. The anomaly calculation asks whether those fermions could form a consistent chiral gauge theory. We use the standard all-left convention: right-handed particles are rewritten as left-handed antiparticles, so their hypercharges change sign.

<sup>1</sup>In the substrate the weak interaction is the zero-controlled CNOT  $\mathcal{C}$  that flips  $I_3$  when  $\chi = 0$ ; a direct enumeration confirms  $\mathcal{C}$  acts on no other bit, so  $I_3$  is forced as the  $T_3$  target.

Work in the all-left convention: a right-handed Weyl state ( $\chi = 1$ ) is replaced by its charge-conjugate left-handed state with effective hypercharge  $Y_{\text{eff}} = -Y$  and conjugate colour rep. Write  $Y_{\text{eff}} = Y$  for  $\chi = 0$  and  $-Y$  for  $\chi = 1$ . The six anomaly-cancellation conditions for one generation are

$$A_1 [SU(3)^2 U(1)] : \sum_{\text{colour triplets}} Y_{\text{eff}} = 0, \quad (9)$$

$$A_2 [SU(2)^2 U(1)] : \frac{1}{2} \sum_{\text{doublets}} Y_{\text{eff}} = 0, \quad (10)$$

$$A_3 [U(1)^3] : \sum_{\text{all}} Y_{\text{eff}}^3 = 0, \quad (11)$$

$$A_4 [\text{grav}^2 U(1)] : \sum_{\text{all}} Y_{\text{eff}} = 0, \quad (12)$$

$$A_5 [SU(3)^3] : n(\mathbf{3}) - n(\bar{\mathbf{3}}) = 0, \quad (13)$$

$$A_6 [SU(2) \text{ Witten}] : \#\text{doublets} \equiv 0 \pmod{2}. \quad (14)$$

**Proposition 1** (Cancellation). *On the 45-codeword content of Section 2, with charges from Section 3, all six conditions vanish identically (per generation), as does the chiral  $U(1)$  trace difference  $\sum Q_L^3 - \sum Q_R^3$ . Equivalently  $\sum Q = 0$ ,  $\sum Q^2 = 16$  (the QED  $\beta$ -function coefficient summed over Weyl states with colour multiplicity, three generations), and  $\sum Q_L^3 = \sum Q_R^3 = -\frac{2}{9}$  per generation.*

*Verification.* Direct exact-rational enumeration over the 256 codewords with the constraints applied; all sums evaluate to 0 (and 16,  $-2/9$ ) as stated. The computation is a few lines and is reproducible.<sup>2</sup> Worked example,  $A_2$  over  $\chi = 0$  states per generation:  $2(-\frac{1}{2}) + 6(\frac{1}{6}) = 0$  (two lepton-doublet members at  $Y = -\frac{1}{2}$ , six quark-doublet members at  $Y = \frac{1}{6}$ ).  $\square$

Proposition 1 only reproduces a known fact. The substantive content is that the *content* is special, to which we now turn.

## 5 Forcedness and non-genericity

The worry that anomaly cancellation might be “built in” is natural. If we choose the charges after the fact, of course we can choose them to cancel. The tests below are designed to avoid that circularity. They hold the charge readout fixed and ask whether the finite content itself is special. The answer is yes: most comparable Boolean contents are anomalous, and the load-bearing parameters are pinned.

**Proposition 2** ( $N_c = 3$  is forced). *Hold the SM rep pattern fixed and treat the number of colours  $N_c$  (the quark colour multiplicity) as free. Then*

$$A_2 = \frac{N_c}{6} - \frac{1}{2}, \quad A_3 = \frac{3 - N_c}{4}, \quad (15)$$

*each vanishing only at  $N_c = 3$ . Anomaly cancellation thus forces three colours.*

*Proof.* With one quark doublet of  $N_c$  colours at  $Y = \frac{1}{6}$  and the lepton doublet at  $Y = -\frac{1}{2}$ ,  $A_2 = \frac{1}{2}(N_c \cdot \frac{1}{6} \cdot 2 + (-\frac{1}{2}) \cdot 2) \cdot \frac{1}{2}$  reduces to  $N_c/6 - 1/2$ ; the cubic trace gives  $A_3 = (3 - N_c)/4$  after substituting the (forced) singlet hypercharges. Both are linear/affine in  $N_c$  with the unique common root  $N_c = 3$ .  $\square$

<sup>2</sup>target\_a\_genericity.py; exact Fraction arithmetic.

**Remark 1** (Independent corroboration of  $N_c = 3$ ). *The substrate fixes  $N_c = 3$  independently of anomalies, in three mutually consistent ways: the three non-zero vectors of  $\mathbb{F}_2^2$  (the colour bits) under  $R3$ ; the complete graph  $K_3$  that is the strong-channel adjacency operator  $V_{\text{strong}} = A_{K_3}$ ; and the  $\mathbb{Z}_3$  triality realised as the order-3 subgroup of  $\text{Aut}(\mathbb{F}_2^2) = \text{GL}(2, \mathbb{F}_2) \cong S_3$  (a symmetry of the colour bits, sufficient for  $3 \leftrightarrow \bar{3}$ ), promoted for gauging to an explicit qutrit clock/shift centre compensator. That anomaly cancellation also demands  $N_c = 3$  (Proposition 2) is independent corroboration.*

**Proposition 3** (colour weight forced). *With the charge written  $Q = \frac{1}{2}Z_f + b\Sigma_c + \frac{1}{2}$  (the historical packaging,  $\Sigma_c$  the colour contribution) and the SM content fixed,  $A_2 = 6 - 18b$ , so anomaly cancellation forces the colour weight  $b = \frac{1}{3}$  uniquely.*

**Proposition 4** (non-genericity, role-symmetry, and neutrality). *Computed over the 256-codeword space with the charge map fixed:*

- (a) *Among the 255 non-empty Boolean “sector rules” for the matter/colour labels, only 2 ( $\approx 0.8\%$ ) are fully anomaly-free; the SM content is one of them.*
- (b) *All 3360 permutations of which bits play the roles  $\{I_3, \chi, \text{colour pair}, \text{LQ}\}$  are anomaly-free and SM-isomorphic: the role assignment is a relabelling symmetry, not a tunable choice (selecting any five role-bits and enumerating their values yields the identical structure).*
- (c) *The generation constraint  $R1$  (any Boolean function of  $(G_0, G_1)$ ) and the weak constraint  $R2$  (any relation of  $W$  to the other bits) are anomaly-neutral: cancellation is per-generation, and  $W$  does not enter the charges or reps.*

*Verification.* Exact enumeration.<sup>3</sup> (a) gives 2/255; (b) gives 3360/3360 identical anomaly multisets; (c) gives all non-empty  $R1, R2$  variants anomaly-free.  $\square$

Proposition 4 is the heart of the matter. Anomaly-freedom is *not* automatic: it is a  $\sim 1\%$  property of comparable contents, pinned to  $N_c = 3$  and to the chiral content. The role permutations being a symmetry means there is no hidden tuning in the bit-to-physics dictionary; the generation/weak neutrality means the discriminating structure lives entirely in the colour/isospin/chirality content selected by  $R3$  and the  $\nu_R$ -removal  $R4$ .

**Theorem 1** (Reduction). *Given the substrate’s representation content—one  $SU(2)$  quark doublet in  $N_c = 3$  colours, singlets  $u_R, d_R$ , a lepton doublet and  $e_R$ , with the chiral  $(B - L)$  residual forcing one right-handed neutrino per generation—anomaly cancellation determines the hypercharges uniquely, up to overall normalisation, as the SM values. This is the classical Geng–Marshak / Minahan–Ramond–Warner theorem [3, 4]. The substrate’s contribution is to derive that special content, including the  $\nu_R$ , from the four Boolean rules  $R1$ – $R4$ .*

**Remark 2** (the  $(B - L)$  residual and  $\nu_R$ ). *Minahan–Ramond–Warner showed that without a right-handed neutrino the SM anomaly conditions admit two hypercharge solutions; uniqueness is restored by adding  $\nu_R$  [4, 3]. In the substrate the 24-left/21-right chiral imbalance of  $R1$ – $R4$  yields a non-zero  $\sum(B - L) = +3$  (+1 per generation), which is precisely the statement that gauge closure requires one extra Weyl state per generation with  $(B - L) = -1$ —uniquely the  $\nu_R$ , excluded from the active code by  $R4$  to preserve the error-correcting distance. The classical uniqueness condition is thus met structurally.*

<sup>3</sup>target\_a\_genericity.py, target\_a\_genericity\_full.py, and target\_a\_colour\_count.py.

## 6 Significance, and what it is not

**The compression.** Counting inputs and outputs: four Boolean constraints on an 8-bit code (plus the colour-blind charge rule) reproduce, as *forced* consequences, the SM fermion multiplicities, the charge quantisation pattern, the value  $N_c = 3$ , and the vanishing of all six anomaly conditions—facts that in the SM are logically independent inputs or “remarkable” consistency conditions. This is a genuine reduction of description length: several independent facts collapse to a short rule that does not merely permit them but is non-generically selected to entail them (Section 5).

**The periodic-table analogy, made precise.** The aptness of the comparison is specifically to Mendeleev’s table as an *organising compression*: it took a list of elements with independent-looking chemical properties and exhibited them as consequences of a single periodic structure, turning coincidences into necessities. The present result does the same for a corner of the SM: anomaly cancellation, normally a coincidence the charges satisfy, becomes a necessity of the code. We stress the *disanalogies*, which bound the claim:

- (i) *Prediction.* The periodic table predicted *new* elements (gallium, germanium). The present result *reproduces* known SM facts; it is retrodiction/organisation, not novel prediction. The genuinely forward, falsifiable content of the wider programme lies elsewhere and is weaker.
- (ii) *Independent confirmation of the substrate.* Atoms and electron shells—the deeper basis of periodicity—were later independently confirmed. The code substrate here is *posited*; the result is derived *within* its axioms, which are not assumption-free.

**Epistemic status.** In the terminology we have found useful, this is *insight into the structure of what we already know*—why a set of SM facts hang together, derived from fewer principles—rather than *insight into nature* (a novel, confirmed empirical prediction). The periodic table was eventually both; this result is, so far, the former. That is a real and non-trivial thing for a model to achieve, and it is the honest ceiling of the claim.

**Open items.** The following are *not* closed and should not be read into the above. (a) The full strong-coupling  $SU(3)$  colour gap (a confining, mirror-coupled non-abelian calculation) is open; the  $\mathbb{Z}_3$  centre compensator supplies the centre algebra only. (b) The number of generations is a declared *input* (R1), not derived. (c) The global  $\mathbb{Z}_3$  colour symmetry of the full walk operator reduces to colour conservation; an explicit bridge-rotation check remains. (d) The result is a statement about the model’s internal logic; it inherits the standard caveat that a proof is conditional on its axioms.

This paper should therefore be read alongside the wider canon updates [11, 12, 13]. Those papers give the broader finite-QEC reconstruction, the matter/gauge ledger, and the current status of which results are closed, conditional, or still open.

## 7 Conclusion

Anomaly cancellation in the Standard Model, together with  $N_c = 3$  and the charge-quantisation pattern, follows as a forced, non-generic, CPT-covariant consequence of four Boolean constraints on an  $[8, 4, 4]$  code, reducing to the classical anomaly  $\Rightarrow$  hypercharge theorem with the special fermion content (including  $\nu_R$  via a  $(B - L)$  residual) now *derived* rather than assumed. This is a compression result in the organising spirit of the periodic table, and—stated honestly—no more than that: it reorganises known physics from fewer principles, it does not predict new

physics, and it stands on posited axioms. Within those bounds, it converts a celebrated SM “coincidence” into a structural necessity.

**Reproducibility.** The public companion code is in the project repository [14], under `scripts/matter_gauge_spectroscopy/`. The local audit ledger is `proof_targets.md`; the canon entries are ANCHOR.md §2.8 and §2.11, with the matching DRIFT entry “C, 2026-06-28”. The principal scripts are:

Script	Purpose
<code>target_a_genericity.py</code>	Exact-rational check of the 45 admitted Weyl codewords, anomaly sums, colour-weight scan, and genericity over sector rules.
<code>target_a_genericity_full.py</code>	Larger role-permutation and $R1/R2$ neutrality sweep.
<code>target_a_colour_count.py</code>	Independent $N_c$ and colour-weight anomaly scan.
<code>target_a_q1q2_cpt.py</code>	CPT check showing why the earlier one-hot colour readout is not acceptable.
<code>z3_colour_resolution.py</code>	$\mathbb{Z}_3$ colour-centre and triality audit.
<code>z3_global_symmetry.py</code>	Global colour-conservation and walk-symmetry audit.

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