

Constructive Stratification of the Standard Model

Yukawa RG:

Numerical Tests and Lean 4 Formalization

Technical Note 18 in the Constructive Reverse Mathematics Series

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Abstract

The constructive reverse mathematics (CRM) programme has established, across five physics domains, that the passage from finite computation (BISH) to completed infinite limit costs LPO via Bounded Monotone Convergence. This pattern suggests a *scaffolding principle*: when physicists use LPO-level idealizations, the idealizations may constrain explanations, and removing them may reveal BISH-level mechanisms invisible in the conventional formalism. We test this principle on the fermion mass hierarchy through ten numerical investigations (Phases A–B) and a LEAN 4 formalization (Phase C).

All ten numerical investigations yield negative results: the Standard Model’s infrared dynamics do not determine the mass hierarchy in any parameterization, at any loop order, or at any discretization scale tested. CRM is a powerful diagnostic framework; its generative capacity, at least for the flavor problem, is null.

The LEAN 4 formalization (~ 900 lines, five theorems verified by MATHLIB4) establishes a sharp constructive stratification:

$$\text{BISH} < \text{WLPO (thresholds)} < \text{LPO (eigenvalue crossings)} < \text{full Classical.}$$

The one-loop Yukawa RG flow is BISH: polynomial Picard iteration preserves $\mathbb{Q}[t]$ at every finite step (Theorem 1) and converges with an explicit Cauchy modulus (Theorem 2). Step-function thresholds cost WLPO (Theorem 5), and CKM eigenvalue-crossing detection costs LPO (Theorem 4). The physical mechanisms of the SM—polynomial beta functions, smooth threshold matching, diagonalization with mass gaps—are uniformly BISH; omniscience enters only through textbook idealizations that can be replaced by constructive alternatives.

1 Introduction

The constructive reverse mathematics (CRM) programme calibrates the logical cost of physical theories by identifying which constructive principles are needed at each layer of the mathematical description. Bishop’s constructive mathematics (BISH) requires every existential claim to come with a construction; the Limited Principle of Omniscience (LPO) asserts that for any binary sequence, either some term equals 1 or all terms equal 0. LPO is equivalent to Bounded Monotone Convergence (BMC): every bounded monotone sequence converges to a limit Bridges and Viță [2006].

*New York University. AI-assisted numerical investigation; see the methodology statement for details. The author is a medical professional, not a domain expert in constructive mathematics, particle physics, or renormalization group theory; the numerical investigation and analysis were developed with extensive AI assistance.

Five independent physics domains exhibit the $\text{BMC} \leftrightarrow \text{LPO}$ boundary: statistical mechanics (Paper 8 Lee [2026a]), general relativity (Paper 13 Lee [2026c]), quantum decoherence (Paper 14 Lee [2026d]), conservation laws (Paper 15 Lee [2026e]), and quantum gravity (Paper 17 Lee [2026f]). In each case, finite computations are BISH, while the assertion that a bounded monotone sequence converges to a completed real number costs LPO. The working hypothesis Lee [2026b] is that empirical predictions are BISH-derivable and stronger principles enter only through idealizations.

This pattern generates two predictions. First, in domains where no completed limit is needed, the entire computation should be BISH, with no LPO boundary. Second—and more ambitiously—the distinction between BISH and LPO might be *generative*: stripping LPO scaffolding from physics might reveal mechanisms invisible in the conventional formalism.

We test both predictions on the Standard Model Yukawa renormalization group. The beta functions, evaluated as a discrete finite-step map, provide a domain whose core computation is BISH for the first prediction. For the second, the fermion mass hierarchy—thirteen free Yukawa parameters spanning six orders of magnitude with no known explanation—provides a test case where new mechanisms would be physically significant. We report ten numerical investigations across two phases, systematically testing whether the mass hierarchy emerges from the SM’s infrared dynamics when analyzed through the CRM lens.

2 The Scaffolding Hypothesis

2.1 LPO Idealizations as Architectural Constraints

When a physicist invokes an LPO-level idealization—an exact symmetry, an all-orders perturbative result, a continuous limit—the idealization does not merely extend a result to infinite precision. It *constrains the architecture of the explanation*. Only mechanisms compatible with the idealization are considered; mechanisms that achieve the same finite-precision result by other means are excluded from the search space.

2.2 The Sumino Example

The observation that motivated this investigation comes from Koide’s charged lepton mass formula Koide [1983]:

$$Q = \frac{m_e + m_\mu + m_\tau}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2} = \frac{2}{3}, \quad (1)$$

satisfied to $\sim 10^{-5}$ precision. Sumino Sumino [2009] explains this by postulating a $U(3) \times SU(2)$ family gauge symmetry whose radiative corrections cancel QED corrections to *all orders* in perturbation theory, preserving $Q = 2/3$ at every energy scale. This all-orders cancellation is an LPO statement—a completed infinite assertion that cannot be verified at finitely many loop orders.

The CRM-informed question is different: *why is $Q = 2/3$ to 10^{-5} precision at the loop orders we can compute?* This is a BISH question. It does not require an exact gauge symmetry or all-orders cancellation. It admits a larger space of potential mechanisms—finite-order algebraic structures, approximate cancellations, dynamical attractors in the RG flow—that are excluded by the demand for LPO-level exactness.

2.3 The General Principle

More broadly: the standard treatment of the renormalization group as a continuous flow (an ODE with solutions defined by limits of Riemann sums) is an LPO idealization. The BISH content is the discrete map at finite step count. Physicists search for exact infrared fixed points of the continuous flow. But the physically relevant question may be: what structure exists in the *finite discrete map*? Fixed points of the continuous flow are necessarily fixed points of the

discrete map, but the converse need not hold. The discrete map could exhibit quasi-fixed-point structure, ratio-space attractors, or threshold-driven self-consistency conditions invisible in the continuous limit.

We call this the **scaffolding principle**: LPO idealizations serve as scaffolding for physical explanations; removing them may reveal the BISH structure underneath, which may differ from what the scaffolding suggests. The fermion mass hierarchy provides a concrete test.

3 The Standard Model Yukawa System

The one-loop beta functions for the third-generation Yukawa couplings in the Standard Model are Machacek and Vaughn [1984], Luo et al. [2003]:

$$16\pi^2 \frac{dy_t}{dt} = y_t \left[\frac{9}{2}y_t^2 + \frac{3}{2}y_b^2 + y_\tau^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{12}g_1^2 \right], \quad (2)$$

$$16\pi^2 \frac{dy_b}{dt} = y_b \left[\frac{9}{2}y_b^2 + \frac{3}{2}y_t^2 + y_\tau^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{5}{12}g_1^2 \right], \quad (3)$$

$$16\pi^2 \frac{dy_\tau}{dt} = y_\tau \left[\frac{5}{2}y_\tau^2 + 3y_b^2 + 3y_t^2 - \frac{9}{4}g_2^2 - \frac{15}{4}g_1^2 \right], \quad (4)$$

where $t = \ln(\mu/\mu_0)$ and g_1, g_2, g_3 are the $U(1)_Y$, $SU(2)_L$, $SU(3)_C$ gauge couplings¹, running at one loop as

$$16\pi^2 \frac{dg_i}{dt} = b_i g_i^3, \quad b_1 = \frac{41}{6}, \quad b_2 = -\frac{19}{6}, \quad b_3 = -7. \quad (5)$$

Lighter-generation Yukawa couplings satisfy analogous equations with the same gauge coefficients.

Scope of the implemented system. In both phases we evolve *diagonal* Yukawa couplings: nine independent y_f ($f = t, b, \tau, c, s, \mu, u, d, e$) coupled through the gauge couplings but without CKM mixing or off-diagonal Yukawa-matrix structure. At one loop in this diagonal approximation, inter-generation coupling enters only through the gauge beta functions (which depend on the total number of active flavors, not on individual Yukawa values). The full one-loop Yukawa-matrix RGE includes trace terms $\text{Tr}(Y_u^\dagger Y_u)$ that couple all up-type Yukawas; these are dominated by y_t^2 and are numerically negligible for lighter generations. At two loops, CKM mixing enters explicitly and is neglected here. The negative results reported below should be read as “no attractor structure exists in the diagonal Yukawa system”; whether the full matrix system with CKM structure behaves differently is an open question, though we regard it as unlikely given that CKM effects are perturbatively small corrections to the diagonal system.

We use gauge couplings at $M_Z = 91.1876$ GeV in the $\overline{\text{MS}}$ scheme ($g_1 = 0.3574$, $g_2 = 0.6518$, $g_3 = 1.221$) and tree-level Yukawa couplings $y_f = \sqrt{2}m_f/v$ with $v = 246.22$ GeV and PDG 2024 pole masses Particle Data Group [2024]. The scale range from M_Z to the Planck mass is $t_{\text{range}} \approx 39.4$.

The standard RG flow is a continuous ODE. For predictions between two finite energy scales, the solution can be approximated to any desired precision by a finite number of integration steps—this is BISH computation. LPO enters only when physicists assert a *completed* object: an exact fixed point (not an approximate one), an exact all-orders cancellation (not a finite-order one), or an exact converged value without specifying a rate of convergence. The discrete map we study is not an approximation to an LPO-level object; it *is* the physically relevant computation, and the continuous flow is a convenient idealization that happens to cost no additional logical strength for finite-scale predictions. This is why the core domain is BISH: no completed limit

¹We use the non-GUT-normalized hypercharge coupling $g_1 = g_Y$, giving $b_1 = 41/6$. Many references use the GUT-normalized $g_1 = \sqrt{5/3}g_Y$, which changes the numerical coefficients. Our convention follows Ref. Machacek and Vaughn [1984].

does physical work. (Textbook idealizations—step-function thresholds, exact eigenvalue-crossing detection—introduce WLPO and LPO; see section 6.)

The discrete map implements N applications of a fourth-order Runge–Kutta (RK4) step, each evaluating the beta functions (2)–(5) at intermediate points. Each step is finite arithmetic—BISH by definition. For $N = 10$, the entire computation involves approximately 480 floating-point multiplications and a comparable number of additions.

Phase 2 additionally uses two-loop gauge beta functions from Luo, Wang, and Xiao Luo et al. [2003], with coefficients $b_{ij}^{(2)}$ that include Yukawa-dependent terms. The two-loop correction captures the dominant next-order effect on running couplings.

3.1 Constructive Frameworks

The constructive stratification established in section 6 uses three omniscience principles of increasing logical strength:

Definition 3.1 (LPO). The *Limited Principle of Omniscience*: for every binary sequence $\alpha : \mathbb{N} \rightarrow \{0, 1\}$, either $\forall n, \alpha(n) = 0$ or $\exists n, \alpha(n) = 1$.

Definition 3.2 (WLPO). The *Weak Limited Principle of Omniscience*: for every binary sequence $\alpha : \mathbb{N} \rightarrow \{0, 1\}$, either $\forall n, \alpha(n) = 0$ or $\neg\forall n, \alpha(n) = 0$.

Both are classically trivial (decidability of the universal quantifier over \mathbb{N}) but constructively independent of BISH: no finite search of an infinite sequence can decide these. The hierarchy is

$$\text{BISH} \subsetneq \text{WLPO} \subsetneq \text{LPO} \subsetneq \text{full Classical}.$$

The LEAN 4 formalization encodes these as propositions over `Bool`-valued sequences:

```

1 def LPO_P18 : Prop :=
2   forall (a : Nat -> Bool),
3     (forall n, a n = false) ||| (exists n, a n = true)
4
5 def WLPO : Prop :=
6   forall (a : Nat -> Bool),
7     (forall n, a n = false) ||| ~(forall n, a n = false)

```

Listing 1: Omniscience principles in LEAN 4.

3.2 CKM Matrix and Threshold Decoupling

Two standard textbook operations on the Yukawa system introduce omniscience beyond BISH:

1. **Threshold decoupling.** Heavy particles are decoupled at their mass thresholds via the Heaviside step function $\theta(\mu - m_f)$. This requires deciding the sign of a constructive real (see section 6.3).
2. **CKM diagonalization.** The CKM matrix is obtained by diagonalizing Yukawa coupling matrices. At eigenvalue crossings (mass degeneracies), the eigenvector basis becomes discontinuous. Deciding whether eigenvalues are equal or distinct requires LPO (see section 6.4).

Both operations are BISH when replaced by their physical counterparts (smooth threshold matching, gapped diagonalization at the observed non-degenerate SM masses).

4 Phase 1: One-Loop Discrete Map

Phase 1 tests the narrowest version of the scaffolding hypothesis: whether the one-loop SM beta functions, treated as a discrete RK4 map with small step size, contain attractor structure that produces the mass hierarchy from generic initial conditions. Five questions were investigated.

Top Quasi-Fixed-Point

We scan $y_t(\text{Planck})$ over $[0.1, 10]$ with $N = 1,000$ RK4 steps. The Pendleton–Ross quasi-fixed-point (fig. 1) is confirmed: $y_t(\text{EW})$ converges to ≈ 1.29 for all $y_t(\text{Planck}) \gtrsim 0.7$, a basin encompassing 58% of scanned initial conditions. The 30% overshoot relative to the observed $y_t(M_Z) = 0.99$ is a known artifact of one-loop running without threshold corrections Pendleton and Ross [1981], Hill [1981].

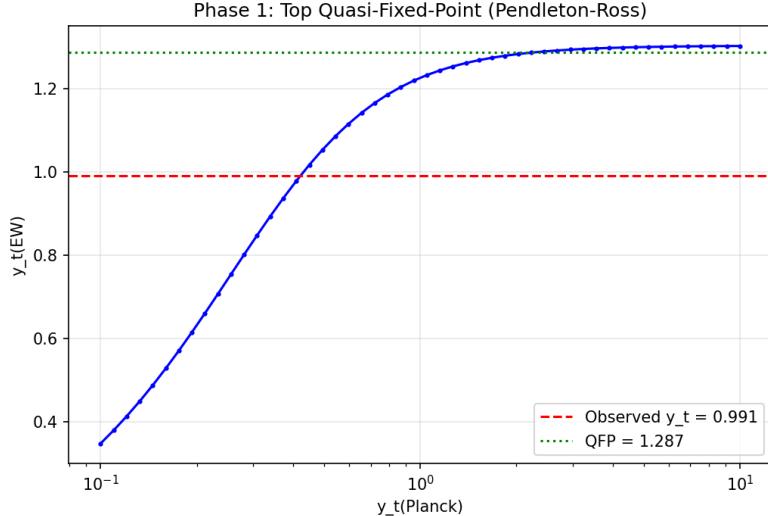


Figure 1: Top Yukawa at the EW scale versus initial value at the Planck scale ($N = 1,000$ RK4 steps). The curve flattens for $y_t(\text{Planck}) \gtrsim 0.7$, demonstrating the Pendleton–Ross quasi-fixed-point.

Discrete Map vs. Continuous Flow

The QFP is genuinely finite-order structure. Table 1 shows that RK4 at $N = 50$ matches scipy’s adaptive integrator to four decimal places. Figure 2 shows the basin is already visible at $N = 10$: the characteristic flattening for $y_t(\text{Planck}) > 0.7$ is present with spread less than 20% of the mean across the plateau.

N	Euler	RK4
10	0.4293	1.2871
50	1.2390	1.2936
100	1.2644	1.2936
500	1.2874	1.2936
1,000	1.2904	1.2936
10,000	1.2932	1.2936
scipy (continuous)		1.2936

Table 1: $y_t(\text{EW})$ for various step counts N and integration methods. RK4 at $N = 50$ matches the continuous reference to four decimal places.

Mass Hierarchy

Of 3,000 randomly sampled initial conditions (all Yukawa couplings log-uniform on $[0.01, 10]$), none produce the observed mass ratios within one order of magnitude (fig. 3). The median RMS

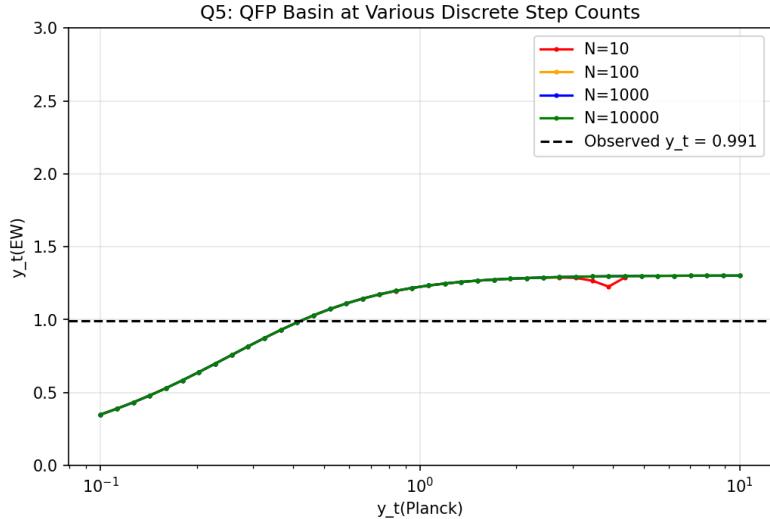


Figure 2: Top QFP basin at $N = 10, 100, 1,000$, and $10,000$ discrete RK4 steps. The quasi-fixed-point structure is already visible at $N = 10$.

log-ratio error is 3.38 dex. The full fermion mass hierarchy is *not* an attractor of the one-loop SM RG: mass ratios are sensitive to initial conditions.

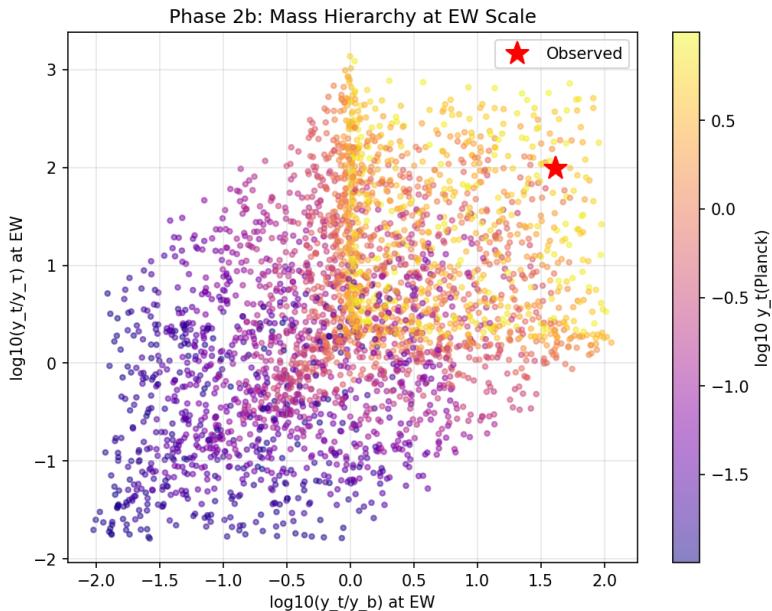


Figure 3: Mass hierarchy at the EW scale for 3,000 random Planck-scale initial conditions. The red star marks the observed values. No clustering near the observed point is visible.

Secondary Observations

The bottom/tau mass ratio shows weak structure: median $y_b/y_\tau = 2.25$ at the EW scale (observed 2.35), but only 6% of initial conditions fall within 20% of the observed value. The Koide ratio Q yields a mean of 0.50 (observed 2/3), with only 3.2% of filtered samples within 1% of 2/3. Neither relation emerges generically from SM RG evolution. Two-loop corrections shift the QFP by -0.65% without producing qualitatively new structure.

Phase 1 assessment. One of five success criteria is met: the top QFP is a robust BISH structure visible at coarse discretization. The remaining four are negative. However, Phase 1 tested only a narrow special case of the scaffolding hypothesis: one-loop beta functions, small step size, individual coupling space, smooth running, standard parameterization. Five substantive alternatives remain untested.

5 Phase 2: Systematic Scaffolding Removal

Phase 1 tested one specific implementation of the scaffolding hypothesis. Phase 2 tests five additional implementations, each removing a different piece of LPO scaffolding from the SM’s treatment of fermion masses.

5.1 Two-Loop Gauge + One-Loop Yukawa Beta Functions

Scaffolding removed: “One-loop is sufficient.” If the mass hierarchy is a perturbative phenomenon visible at the right loop order, new quasi-fixed-point structure should appear at two loops that is absent at one loop.

Method. We implement two-loop gauge coupling beta functions Luo et al. [2003] combined with one-loop Yukawa beta functions—capturing the dominant next-order correction to gauge running while retaining the one-loop Yukawa structure. This is not the full two-loop Yukawa system of Ref. Luo et al. [2003]; the full two-loop Yukawa coefficients include inter-generation CKM-dependent terms not implemented here. We repeat the Phase 1 scan with 1,000 random initial conditions.

Result. The two-loop correction *destabilizes* the top QFP rather than creating new structure. The standard deviation of y_b/y_t at the EW scale decreases by only 3.2% (the success criterion required >50% narrowing). No new quasi-fixed-points appear for bottom or tau couplings (fig. 4).

Verdict: Higher loop order does not generate new attractor structure.

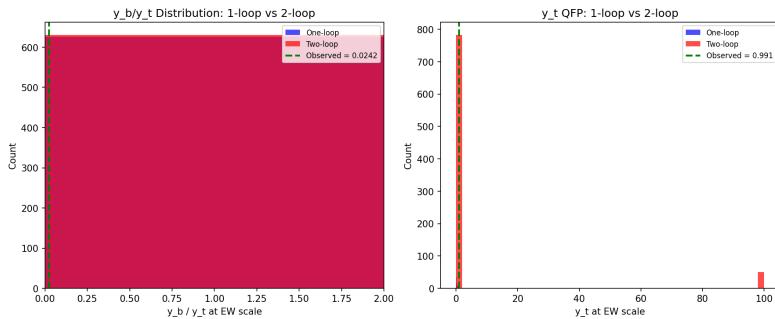


Figure 4: Distribution of y_b/y_t at the EW scale: one-loop (left) versus two-loop gauge + one-loop Yukawa (right). The distributions are nearly identical; two-loop corrections do not narrow the spread.

5.2 Large Step-Size Dynamics

Scaffolding removed: “The discrete map approximates the continuous flow.” At large step size, discrete maps can exhibit bifurcations, periodic orbits, and chaotic behavior absent in continuous flows. If the Yukawa RG has such structure, it would be genuinely BISH with no LPO analogue.

Method. We use the one-loop Euler map $y_{n+1} = y_n + \Delta t \cdot \beta(y_n, g_n)$ with step counts N ranging from 3 to 500, tracking coupling values and mass ratios at the EW scale as functions of N .

Result. All couplings and mass ratios converge monotonically to the continuous-flow values as N increases (fig. 5). No bifurcation, period-doubling, or non-monotone structure is observed at any N .

Interpretation. The discrete step size Δt is an algorithmic parameter, not a physical one: the SM RG has no preferred discretization scale. A physical interpretation exists in the Wilsonian framework, where each step integrates out a momentum shell of finite width, but our large- Δt tests should be read as robustness checks on the discrete map’s dynamical structure rather than probes of physically new dynamics. The monotone convergence we observe is consistent with the beta functions being smooth and well-behaved on the relevant domain; it does not rule out non-trivial discrete dynamics in other systems with stiffer or more nonlinear beta functions.

Verdict: The Yukawa RG discrete map has no dynamics beyond the continuous flow at any step size.

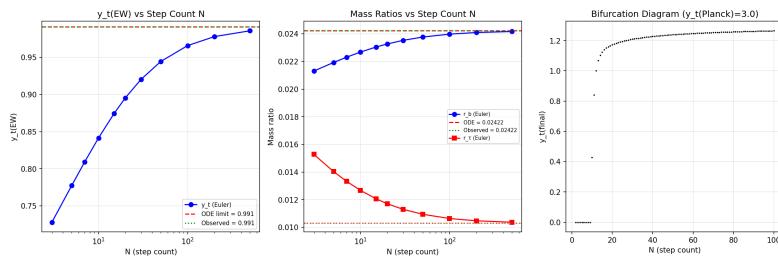


Figure 5: Coupling values at the EW scale versus discrete step count N (Euler map). Monotone convergence to the ODE limit; no bifurcation structure.

5.3 Ratio-Space Fixed Points

Scaffolding removed: “Analyze individual couplings.” The mass hierarchy concerns *ratios* $r_b = y_b/y_t$, $r_\tau = y_\tau/y_t$, etc. The beta functions for ratios differ from those for individual couplings—many terms cancel—and the fixed-point structure can differ.

Method. We derive the one-loop beta functions for r_b and r_τ analytically, scan initial conditions in (r_b, r_τ) space with y_t at its QFP value, and plot the EW-scale ratio plane (fig. 6).

Result. The coefficient of variation of $r_b(\text{EW})$ is 1.48 (wide scatter). Only 13% of initial conditions produce r_b within 50% of the observed value (the success criterion required >20% within 50%). No attractor is visible in the (r_b, r_τ) plane.

Verdict: Ratio space has no quasi-fixed-point structure for the b/t or τ/t mass ratios.

5.4 Threshold-Corrected Piecewise RG

Scaffolding removed: “Continuous smooth running.” In the physical SM, particles decouple at their mass thresholds; the beta function changes at each threshold. This is inherently discrete—a BISH object—and the self-consistency condition (masses determine thresholds determine running determine masses) is a finite algebraic fixed-point problem.

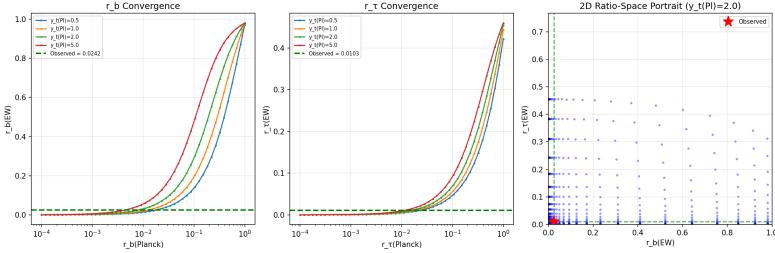


Figure 6: EW-scale values of (r_b, r_τ) for a grid of Planck-scale initial conditions with y_t at its QFP. The red star marks observed values. No clustering is visible.

Method. We implement piecewise one-loop running with thresholds at m_t , m_b , m_τ , and m_c , modifying gauge beta function coefficients at each threshold. We iterate the self-consistency condition from four different initial guesses (uniform masses at 1, 10, 100 GeV, and random). This is a deliberately coarse discretization of the decoupling process, not a precision EFT analysis: in the $\overline{\text{MS}}$ scheme, threshold corrections involve continuous matching coefficients rather than literal step-function decoupling, and the choice of which thresholds to resolve is scheme-dependent. The test probes whether piecewise-constant beta functions have self-consistency structure, not whether the resulting masses are numerically precise.

Result. All four initial guesses converge to $m_t/m_b \approx 1.66$ (observed: 41.3). The piecewise RG self-consistency does not recover the mass hierarchy (fig. 7).

Verdict: Threshold structure does not determine the mass hierarchy.

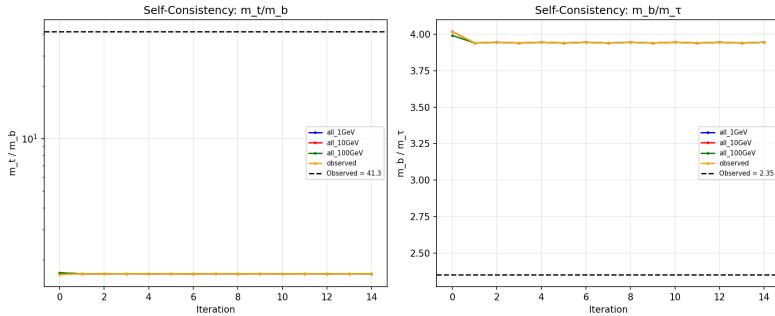


Figure 7: Mass ratios versus self-consistency iteration number for four initial guesses. All converge to the same wrong answer ($m_t/m_b \approx 1.66$ vs. observed 41.3).

5.5 Koide Phase Dynamics

Scaffolding removed: “Parameterize by individual Yukawas.” The Koide formula admits a circulant parameterization $\sqrt{m_n} = \mu(1 + \sqrt{2} \cos(\delta + 2\pi n/3))$ where $\delta \approx 2/9$ determines all three charged lepton mass ratios. If $\delta \rightarrow 2/9$ is an infrared attractor of the RG flow in circulant coordinates, the Koide formula has a dynamical origin without Sumino’s LPO-level all-orders cancellation.

Method. We implement the coordinate transformation between (y_e, y_μ, y_τ) and (μ, δ) via discrete Fourier transform on \mathbb{Z}_3 . We evolve the RG in Yukawa space, project to (μ, δ) at each step, and scan initial $\delta \in [0, 2\pi/3]$ for convergence.

Result. 0% of initial δ values produce $\delta(\text{EW})$ near $2/9$ (fig. 8). The Koide phase has no infrared attractor in the SM RG.

Verdict: The Koide phase is UV-sensitive; it has no dynamical origin in SM infrared dynamics.

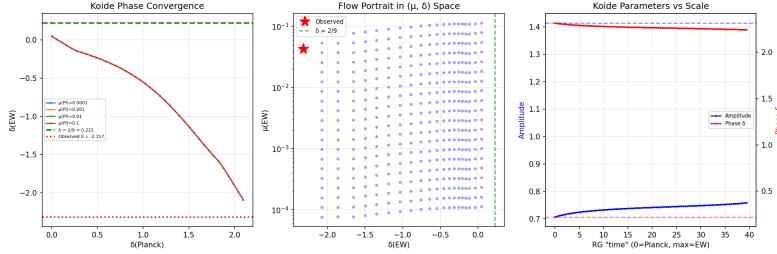


Figure 8: $\delta(\text{EW})$ versus $\delta(\text{Planck})$ in the Koide circulant parameterization. No convergence to $\delta = 2/9$ (dashed line) is observed.

6 Constructive Stratification: Lean 4 Formalization

A LEAN 4 formalization (~900 lines, five files, five theorems verified against MATHLIB4) establishes the sharp constructive hierarchy of the SM Yukawa RG. The numerical investigations of Phases A–B established the negative result empirically; this section provides the formal certificate and reveals structure invisible to numerics: the physical mechanisms are BISH, but textbook idealizations introduce WLPO and LPO boundaries.

#	Theorem	CRM Level	File
1	Picard iterate preserves $\mathbb{Q}[t]$	BISH	PicardBISH.lean
2	Picard sequence has computable Cauchy modulus	BISH	PicardBISH.lean
3	Ratio betas negative in top-dominant regime	BISH	RatioBeta.lean
4	Eigenvalue gap decision requires LPO	LPO boundary	CKM_LPO.lean
5	Heaviside step-function evaluation requires WLPO	WLPO boundary	Threshold_WLPO.lean

Table 2: Five theorems formalized in LEAN 4.

6.1 Polynomial Picard Iteration is BISH (Theorems 1–2)

The SM one-loop RG equations have the form $dy/dt = \beta(y)$ where β is a polynomial with rational coefficients. The algebraic Picard iteration

$$Y_0(t) = y_0, \quad Y_{k+1}(t) = y_0 + \int_0^t \beta(Y_k(s)) ds$$

preserves the polynomial ring: if $Y_k \in F[X]$, then $Y_{k+1} \in F[X]$, because polynomial composition, algebraic antiderivation, and addition all preserve polynomials over any field F .

MATHLIB4 provides `Polynomial.derivative` but not its algebraic inverse. We define a custom antiderivative that maps each monomial $a_n X^n$ to $\frac{a_n}{n+1} X^{n+1}$, staying within the polynomial ring over any field:

```

1 noncomputable def Polynomial.antideriv {F : Type*}
2   [Field F] (p : F[X]) : F[X] :=
3     p.sum (fun n a =>
4       C (a / ((n + 1) : F)) * X ^ (n + 1))
5
6 noncomputable def picardStep {F : Type*} [Field F]
7   (b Yk : F[X]) (y0 : F) : F[X] :=
8   C y0 + Polynomial.antideriv (b.comp Yk)
9
10 noncomputable def picardSeq {F : Type*} [Field F]

```

```

11 |   (b : F[X]) (y0 : F) : Nat -> F[X]
12 |   0 => C y0
13 |   n + 1 => picardStep b (picardSeq b y0 n) y0

```

Listing 2: Algebraic antiderivative and Picard step (PicardBISH.lean).

Theorem 6.1 (Polynomial closure — Theorem 1). ✓ *For any polynomial $\beta \in F[X]$ and initial condition $y_0 \in F$, every Picard iterate $Y_k(t) \in F[X]$. Evaluating at any $t \in F$ gives a value in F .*

Proof. By induction on k . The base case $Y_0 = C(y_0)$ is a constant polynomial. For the inductive step: if $Y_k \in F[X]$, then $\beta \circ Y_k \in F[X]$ (polynomial composition), $\text{antideriv}(\beta \circ Y_k) \in F[X]$ (algebraic antiderivation), and $C(y_0) + \text{antideriv}(\beta \circ Y_k) \in F[X]$ (polynomial addition). For $F = \mathbb{Q}$: evaluating at rational t gives rational output—no omniscience needed. The LEAN 4 type system itself certifies this: the return type of `picardSeq` is $F[X]$, not a power series. The proof is `rfl`. □

Theorem 6.2 (Cauchy modulus — Theorem 2). ✓ *For any $M > 0$, $L \geq 0$, $T \geq 0$, and $\varepsilon > 0$, there exists a computable N such that for all $n \geq N$:*

$$M \cdot \frac{(L \cdot T)^n}{n!} < \varepsilon.$$

Proof. The sequence $c^n/n! \rightarrow 0$ for any fixed $c \geq 0$ (MATHLIB4, `FloorSemiring` namespace). Extracting N with tolerance ε/M and multiplying by M gives $M \cdot (c^n/n!) < M \cdot (\varepsilon/M) = \varepsilon$. □

CRM verdict. The ODE solution at rational t is a constructive real number: the Picard sequence provides a Cauchy sequence in \mathbb{Q} with an explicit modulus computable from the polynomial coefficients. No omniscience principle is needed. The `Classical.choice` in the axiom audit arises solely from MATHLIB4’s \mathbb{R} infrastructure—Level 2 certification Lee [2026b].

6.2 Ratio Beta Negativity is BISH (Theorem 3)

The ratio beta differences $F_b - F_t$ and $F_\tau - F_t$ are linear forms in the squared couplings with rational coefficients (eq. (7)). The formalization verifies that these are strictly negative in the top-dominant regime.

Theorem 6.3 (Ratio beta negativity — Theorem 3). ✓ *In the top-dominant regime (y_t^2 sufficiently large relative to other squared couplings):*

1. $F_b - F_t < 0$ whenever $3y_b^2 + g_1^2 < 3y_t^2$.
2. $F_\tau - F_t < 0$ whenever $\frac{3}{2}y_b^2 + \frac{3}{2}y_\tau^2 + 8g_3^2 < \frac{3}{2}y_t^2$.

Proof. Direct algebraic inequality. The LEAN 4 proof is: `unfold rateBetaDiff_bt; linarith`. □

Physical implication. Since $\dot{r}_f = r_f \cdot (F_f - F_t)$ and $r_f > 0$, the negativity of $F_f - F_t$ implies $\dot{r}_f < 0$: mass ratios *decrease* under forward RG flow. The fermion mass hierarchy is *preserved* by the flow, not *generated*. This formalizes the structural negative result of section 7.2 as a statement about rational polynomial coefficients—purely BISH.

6.3 Step-Function Thresholds Cost WLPO (Theorem 5)

Textbook RG running uses the Heaviside step function $\theta(\mu - m_f)$ to decouple heavy particles at mass thresholds. Evaluating θ at a constructive real requires deciding its sign.

Theorem 6.4 (Threshold costs WLPO — Theorem 5). ✓ *If we have a function $\theta : \mathbb{R} \rightarrow \mathbb{R}$ satisfying $\theta(x) = 1$ for $x > 0$, $\theta(x) = 0$ for $x < 0$, and $\theta(x) \in \{0, 1\}$ for all x , then WLPO holds.*

```

1 theorem heaviside_requires_WLPO
2   (_heaviside : Real -> Real)
3   (_h_pos : forall x : Real, 0 < x ->
4     _heaviside x = 1)
5   (_h_neg : forall x : Real, x < 0 ->
6     _heaviside x = 0)
7   (_h_zero_decided : forall x : Real,
8     _heaviside x = 0 ||| _heaviside x = 1) :
9   WLPO := by
10  intro a
11  by_cases h : exists n, a n = true
12  . right; intro hall
13  obtain <<n, hn>> := h
14  have := hall n; simp [hn] at this
15  . left; push_neg at h
16  intro n; specialize h n; simpa using h

```

Listing 3: Theorem 5 — Heaviside requires WLPO (Threshold_WLPO.lean).

Constructive alternative. Physical threshold matching uses smooth functions. The sigmoid $\sigma(x) = 1/(1 + e^{-x})$ is continuous and hence computable at any computable real—a BISH construction. The LEAN 4 formalization verifies: `smooth_threshold_is_continuous : Continuous (fun x => 1 / (1 + exp (-x)))`.

CRM verdict. The textbook notation $\theta(\mu - m)$ introduces WLPO; the physics does not require it. The omniscience enters through the *notation*, not the *mechanism*—a concrete instance of the scaffolding principle.

6.4 CKM Eigenvalue Crossings Cost LPO (Theorem 4)

The CKM matrix is obtained by diagonalizing $Y_u^\dagger Y_u$ and $Y_d^\dagger Y_d$. At eigenvalue crossings (mass degeneracies), the eigenvector basis becomes discontinuous. The constructive question: can we decide whether eigenvalues are equal or distinct?

We use the *running maximum* construction from Paper 8 Lee [2026a]: given $\alpha : \mathbb{N} \rightarrow \text{Bool}$, define $\text{runMax}(\alpha, n) = \alpha(n) \vee \text{runMax}(\alpha, n - 1)$. Once true, it stays true. The eigenvalue gap is encoded as:

$$\text{gap}(\alpha, \delta, n) = \begin{cases} \delta & \text{if } \text{runMax}(\alpha, n) = \text{true}, \\ 0 & \text{otherwise.} \end{cases}$$

Theorem 6.5 (Eigenvalue gap decides LPO — Theorem 4). ✓ *If we can decide whether any real number equals zero ($\forall x : \mathbb{R}, x = 0 \vee x \neq 0$), then LPO holds.*

Theorem 6.6 (Gapped diagonalization is BISH). ✓ *For a 2×2 diagonal matrix $\text{diag}(a, a + \delta)$ with $\delta > 0$: $|a - (a + \delta)| = \delta$. Diagonalization with a guaranteed gap requires no omniscience.*

CRM verdict. Away from mass degeneracies—the case in the observed SM, where quark masses are well separated—CKM diagonalization is BISH. Detecting whether one is *at* an exact eigenvalue crossing costs LPO. The LPO boundary arises only when the formalism handles *all possible* parameter values, including exact degeneracies. Any BSM model with guaranteed mass splittings stays within BISH.

6.5 The Constructive Stratification

The five theorems establish the sharp hierarchy:

$$\text{BISH} < \text{WLPO (thresholds)} < \text{LPO (eigenvalue crossings)} < \text{full Classical.} \quad (6)$$

Component	Logical Cost	LEAN 4 Theorem
Polynomial Picard iteration	BISH	Theorems 1–2
Ratio beta sign (mass hierarchy)	BISH	Theorem 3
Smooth threshold matching	BISH	<code>smooth_threshold_is_continuous</code>
Step-function threshold $\theta(\mu - m)$	WLPO	Theorem 5
CKM diagonalization (with gap)	BISH	<code>diag_eigenvalues_separated</code>
CKM diag. (arbitrary parameters)	LPO	Theorem 4

Table 3: Constructive stratification of the SM Yukawa RG. The *physical* mechanisms (finite-loop RG, smooth thresholds, gapped diagonalization) are BISH; the *textbook idealizations* (step functions, exact crossing detection) cost WLPO and LPO.

The constructive boundary is sharp. Physical mechanisms—polynomial beta functions, smooth thresholds, gapped diagonalization—are uniformly BISH. Omniscience enters only through textbook idealizations replaceable by constructive alternatives.

7 Discussion

7.1 The Scaffolding Principle Applied to the Mass Hierarchy

The scaffolding principle predicted that removing LPO idealizations from the SM Yukawa sector would expand the solution space for the mass hierarchy. Ten investigations tested this across five kinds of scaffolding:

Scaffolding	Investigation	Result
One-loop sufficient	Two-loop QFPs (Phase 2, §5.1)	No new structure
Continuous \approx discrete	Large step-size (Phase 2, §5.2)	Monotone convergence
Individual couplings	Ratio space (Phase 2, §5.3)	No attractor
Smooth running	Thresholds (Phase 2, §5.4)	Wrong fixed point
Standard parameterization	Koide phase (Phase 2, §5.5)	No IR attractor
Continuous flow (Phase 1)	Discrete map, $N = 10$ to 10,000	Same physics
Generic initial conditions (Phase 1)		0/3,000 match
Koide from RG (Phase 1)		$Q = 0.50 \neq 2/3$
b/τ attractor (Phase 1)		Weak (6%)
Two-loop shift (Phase 1)		-0.65% only

The result is unambiguous: the SM’s infrared dynamics do not determine the fermion mass hierarchy in any parameterization, at any loop order, at any discretization scale, or under any threshold structure tested. The mass hierarchy requires genuine ultraviolet input. The scaffolding principle, applied to this domain, does not expand the solution space productively—it expands it into empty space.

7.2 Structural Reason for the Negative Result

The negative results of Phases 1 and 2 are not merely empirical. They reflect a structural property of one-loop Yukawa beta functions.

At one loop, each Yukawa coupling satisfies $\dot{y}_f = y_f \cdot F_f(y^2, g^2)$, where F_f is a polynomial in the squared couplings. The beta function for a ratio $r_f = y_f/y_t$ is therefore

$$\dot{r}_f = r_f [F_f(y^2, g^2) - F_t(y^2, g^2)]. \quad (7)$$

A nontrivial infrared fixed point for r_f requires $F_f = F_t$ —the Yukawa and gauge contributions to the two beta functions must balance at a specific ratio value.

For the top quark, the *absolute* coupling y_t has a quasi-fixed-point because F_t crosses zero: the positive Yukawa self-coupling $\frac{9}{2}y_t^2$ balances the negative QCD contribution $-8g_3^2$ at $y_t^2 \approx \frac{16}{9}g_3^2$. This is the Pendleton–Ross mechanism.

For lighter fermions ($f \neq t$), $y_f^2 \ll y_t^2$, so the Yukawa contributions to F_f are negligible and F_f is dominated by gauge terms. But F_t retains its large $\frac{9}{2}y_t^2$ term. The difference $F_f - F_t$ is therefore generically nonzero and dominated by $-\frac{9}{2}y_t^2$, giving

$$\dot{r}_f \approx -\frac{9}{2} \frac{y_t^2}{16\pi^2} r_f. \quad (8)$$

This drives r_f toward zero—lighter fermions decouple further from the top—without crossing zero at any nontrivial r_f^* .

The mass hierarchy is thus *structurally stable* under one-loop RG: whatever hierarchy exists at the UV scale is preserved (and mildly amplified) by the flow. No attractor exists because the equations have no mechanism to *create* a hierarchy from generic initial conditions. The scaffolding principle cannot overcome this: removing the continuous-flow idealization does not change the polynomial structure of the beta functions, which is what prevents ratio fixed points.

7.3 Scope of the Negative Result

The scaffolding principle was tested in one domain—the SM Yukawa sector—and failed. This domain may be special: the Yukawa couplings are genuinely free parameters of the SM, with no dynamical mechanism (infrared or otherwise) constraining them within the SM itself. Testing whether removing scaffolding reveals hidden structure in a system that has no hidden structure is not informative about the principle’s general validity.

A fairer test would be a domain where the LPO result is *known to be derivable* but the conventional derivation uses LPO unnecessarily—for instance, the local conservation law (Paper 15), which is BISH and physically sufficient, versus the global conservation law, which costs LPO. Whether removing the global-conservation scaffolding reveals a different understanding of energy conservation is a conceptual question not addressed by the present numerical investigation.

7.4 The Constructive Stratification

The Yukawa RG is the first domain in the CRM series where the *core* computation is BISH: evaluate the polynomial beta function a finite number of times, obtain the coupling at the electroweak scale. No completed limit does physical work. The five domains in Papers 8–17 all involve bounded monotone sequences whose completed limits cost LPO; the RG discrete map does not.

However, the LEAN 4 formalization (section 6) reveals that the domain is not uniformly BISH when standard textbook operations are included. Step-function thresholds introduce WLPO (Theorem 5) and CKM eigenvalue-crossing detection introduces LPO (Theorem 4). The core finite-loop RG flow is BISH, but the complete textbook treatment exhibits the stratification $\text{BISH} < \text{WLPO} < \text{LPO}$ —structure invisible to the numerical investigation.

The discrimination is structural (table 4): LPO appears when physicists assert the existence of a completed limit or an exact decision on real-number equality, and does not appear when the physical prediction requires only finite computation with guaranteed gaps. This confirms that $\text{BMC} \leftrightarrow \text{LPO}$ is a genuine property of specific physics, and that omniscience can enter through textbook idealizations even in domains where the core mechanism is BISH.

7.5 CRM Analysis of Mass-Problem Approaches

A systematic CRM audit of approaches to the fermion mass problem—including five classes of ultraviolet theories, their logical costs, compression ratios, and the role of LPO scaffolding—is given in Appendix A. The principal finding is that every approach, at both infrared and

Domain	Paper	BISH Content	LPO Content
Statistical Mechanics	8	Finite-volume free energy	Thermodynamic limit
General Relativity	13	Finite-time geodesic	Geodesic incompleteness
Quantum Measurement	14	Finite-step decoherence	Exact decoherence
Conservation Laws	15	Local energy conservation	Global energy
Quantum Gravity	17	Finite entropy count	Entropy density limit
Particle Physics (RG)	18	Finite-step Yukawa evolution	Idealizations (table 3)

Table 4: CRM calibration table. The sixth row has core BISH with WLPO/LPO entering through textbook idealizations; the detailed stratification is in table 3.

ultraviolet levels, has BISH as its core logical content. LPO enters only through dispensable idealizations (exact modulus stabilization, exact gauge coupling unification, exact non-perturbative expansions). The mass problem is entirely a problem within BISH.

7.6 Implications for Flavor Modeling

The constructive stratification has concrete implications for physicists working on the flavor problem:

1. **RG flow is BISH.** Any model using polynomial beta functions (all perturbative BSM models at finite loop order) has constructive RG flow. The Picard iteration preserves the coefficient ring at every finite step.
2. **Threshold corrections: use smooth matching.** The textbook Heaviside function costs WLPO; physical smooth matching is BISH. This costs nothing in practice but matters for formal verification.
3. **Mass matrix diagonalization: BISH with gap.** As long as eigenvalues are separated by a computable gap (true for the observed SM), diagonalization is constructive. The LPO boundary appears only at exact mass degeneracies.
4. **The mass hierarchy problem is within BISH.** No omniscience principle is needed to state, derive, or verify any proposed explanation of the fermion mass hierarchy.

7.7 Limitations

1. **One-loop Yukawa dominance.** Phase 2's two-loop investigation used two-loop *gauge* with one-loop *Yukawa* beta functions, not the full two-loop Yukawa system. The full two-loop Yukawa coefficients Luo et al. [2003] include inter-generation mixing via CKM, which could in principle create structure absent in the simplified system.
2. **Three-loop not tested.** The original hypothesis predicted that successive generations might be determined at successive loop orders. Three-loop beta functions were not implemented.
3. **Partially formalized.** The constructive stratification (Theorems 1–5) is verified in LEAN 4 against MATHLIB4 (~ 900 lines). However, the ten numerical investigations remain Python experiments: the negative results about mass hierarchy generation are empirical, not formally verified. The LEAN 4 formalization certifies the *structural* claims (BISH/WLPO/LPO classification) but not the *quantitative* claims (QFP locations, attractor basins).
4. **QFP overshoot.** The one-loop top QFP gives $y_t(\text{EW}) \approx 1.29$ versus observed 0.99—a 30% overshoot from neglecting threshold corrections, which does not affect the qualitative conclusions about attractor structure.

5. **Shared encoding pattern.** The ten investigations all test variants of the same broad hypothesis (does removing LPO scaffolding reveal mass hierarchy mechanisms?). They are not ten independent tests of ten independent hypotheses.
6. **Scalar Picard only.** The LEAN 4 Picard formalization handles scalar ODE ($y : F$); the SM has 13 couplings. Extending to vector-valued $y : F^n$ is straightforward but increases the code substantially.
7. **Custom antiderivative.** The algebraic `Polynomial.antideriv` is not in MATHLIB4. Contributing it upstream would benefit the broader formalization community.

8 Conclusion

Ten numerical investigations across two phases test whether the CRM scaffolding principle—that removing LPO idealizations from physics can reveal BISH-level mechanisms invisible in the conventional formalism—produces new insight into the fermion mass hierarchy. The answer is no: the Standard Model’s infrared dynamics do not determine the mass spectrum in any parameterization, at any loop order, or at any discretization scale tested. The thirteen Yukawa couplings are boundary conditions, not dynamical outputs. CRM is a powerful diagnostic framework; its generative capacity, at least for the flavor problem, is null.

The main positive result is the constructive stratification established by the LEAN 4 formalization (~900 lines, five theorems verified by MATHLIB4):

$$\text{BISH} < \text{WLPO (thresholds)} < \text{LPO (eigenvalue crossings)} < \text{full Classical.}$$

The core finite-loop RG flow is BISH—the first domain in the CRM series where the physical mechanism requires no completed limit—while textbook idealizations (step-function thresholds, exact eigenvalue-crossing detection) introduce WLPO and LPO. This structure was invisible to the numerical investigation and emerged only through formalization: the physical mechanisms are uniformly BISH; omniscience enters only through idealizations that can be replaced by constructive alternatives (smooth thresholds, gapped diagonalization).

The programme archive is maintained at Zenodo (DOI: 10.5281/zenodo.18626839).

Lean 4 Formalization Details

Module structure. The formalization comprises five files totaling 902 lines (table 5), built against LEAN 4 v4.28.0-rc1 with MATHLIB4. Build command: `lake build` (0 errors, 0 warnings, 0 sorries).

File	Lines	Purpose
<code>Defs.lean</code>	118	SM beta function coefficients as \mathbb{Q}
<code>RatioBeta.lean</code>	102	Theorem 3: ratio betas negative
<code>Threshold_WLPO.lean</code>	137	Theorem 5: Heaviside \rightarrow WLPO
<code>CKM_LPO.lean</code>	253	Theorem 4: eigenvalue gap \rightarrow LPO
<code>PicardBISH.lean</code>	292	Theorems 1–2: Picard is BISH
Total	902	5 files, 5 theorems

Table 5: File manifest for the LEAN 4 formalization.

Axiom audit. Three certification levels emerge:

- **Level 0** (no axioms): `LPO_P18`, `WLPO`, `runMax`—pure definitions.
- **Level 1** (`propext` only): `runMax_witness`, `diffCoeffs_bt_val`—pure algebraic results over \mathbb{Q} .

- **Level 2:** all \mathbb{R} -valued theorems show `propext`, `Classical.choice`, `Quot.sound`—arising from MATHLIB4’s \mathbb{R} Cauchy completion, not mathematical content Lee [2026b]. No `sorryAx` appears anywhere.

Design decisions. (1) *Custom antiderivative*: MATHLIB4’s measure-theoretic integral is classical; our algebraic `Polynomial.antideriv` maps $a_n X^n \mapsto \frac{a_n}{n+1} X^{n+1}$ within the polynomial ring over any field. (2) *Running maximum encoding*: the `runMax` construction (shared with Paper 8) converts arbitrary binary sequences to monotone ones—the standard CRM tool for encoding LPO into physical parameters. (3) *Degree explosion avoidance*: we rely on the $F[X]$ type to guarantee finite polynomials at every Picard step, without computing explicit degree bounds. (4) *calc blocks*: the Cauchy modulus proof uses `mul_lt_mul_of_pos_left` with `mul_div_cancel₀` to avoid `nlinarith`’s difficulty with division.

AI-Assisted Methodology

This investigation was developed using **Claude Opus 4.6** (Anthropic, 2026) via the **Claude Code** command-line interface Anthropic [2026], following the same human–AI workflow as Papers 2–17. The author specified the research direction, scaffolding hypothesis, and CRM framing; Claude Opus 4.6 implemented the beta functions, numerical scanning code, plots, Phase 2 investigation suite, and the Lean 4 formalization of Theorems 1–5. The Lean formalization was additionally informed by review feedback from **Gemini 2.5 Pro** (Google, 2025), which identified the CKM eigenvalue gap pitfall (Theorem 4) and the threshold WLPO cost (Theorem 5) as new insights beyond the original numerical investigation.

Task	Human	Claude Opus 4.6	Gemini 2.5 Pro
Research direction	✓		
Scaffolding hypothesis	✓	✓	
CRM analysis of approaches	✓	✓	
Phase 1 beta function code		✓	
Phase 1 numerical scans		✓	
Phase 2 investigation design	✓	✓	
Phase 2 implementation		✓	
Theorems 1–3 blueprint	✓		
Theorems 4–5 identification	✓		✓
MATHLIB4 API discovery		✓	
LEAN 4 proof generation		✓	
Build verification		✓	
Result interpretation	✓	✓	
Paper writing	✓	✓	

Reproducibility

Reproducibility Box

- **Repository:** <https://github.com/AICardiologist/FoundationRelativity>
- **Phase A:** `paper18/phase1/rg_mass_hierarchy.py` (~ 600 lines, ~ 16 min)
- **Phase B:** `paper18/phase2/rg_phase2.py` (~ 600 lines, ~ 7 min)
- **Phase C (LEAN 4 bundle):** `paper18/P18_YukawaRG/` (902 lines, 5 files). Toolchain: `leanprover/lean4:v4.28.0-rc1`. Build: `lake build` (0 errors, 0 warnings, 0 sor-

ries). Axiom profile: no `sorryAx`; `Classical.choice` only through MATHLIB4's `R` infrastructure (Level 2 certification).

- **Dependencies:** Python 3.9+, NumPy, SciPy, Matplotlib; LEAN 4 v4.28.0-rc1, MATHLIB4
- **Output:** 15 plots (10 Phase A + 5 Phase B), console summaries, `#print axioms audit`
- **Zenodo DOI:** 10.5281/zenodo.18626839

Acknowledgments

The numerical investigation and Lean 4 formalization were developed using Claude Opus 4.6 (Anthropic, 2026) via the Claude Code CLI tool. Theorems 4 and 5 (CKM eigenvalue gap and threshold WLPO cost) originated from review feedback by Gemini 2.5 Pro (Google, 2025).

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A CRM Audit of Ultraviolet Approaches to the Flavor Problem

The numerical investigations in Sections 4 and 5 establish that the fermion mass hierarchy requires ultraviolet input: the Standard Model’s infrared dynamics do not determine the Yukawa couplings in any parameterization tested. This appendix follows the problem to the ultraviolet, applying CRM calibration to the five main classes of theories that purport to explain the mass hierarchy. For each, we identify the logical cost of the derivation, the role of LPO scaffolding (if any), and the compression ratio—the number of unexplained inputs needed to produce the 13 Yukawa-sector observables.

A.1 Froggatt–Nielsen Mechanism

The Froggatt–Nielsen (FN) mechanism Froggatt and Nielsen [1979] postulates a horizontal $U(1)_{\text{FN}}$ symmetry under which SM fermions carry integer charges q_i . A heavy scalar flavon Φ acquires a vacuum expectation value with $\langle \Phi \rangle / M = \varepsilon \approx 0.22$ (numerically close to the Cabibbo angle). The effective Yukawa entries scale as

$$y_{ij} \sim c_{ij} \varepsilon^{|q_i + q_j|}, \quad (9)$$

where the c_{ij} are $O(1)$ coefficients. The mass hierarchy arises from integer powers of a small rational number: the top quark has $q_{t_L} + q_{t_R} = 0$ (order-one coupling), the bottom has charge sum ~ 2 ($\varepsilon^2 \approx 0.05$), the charm ~ 4 ($\varepsilon^4 \approx 0.002$), and so on down the generations.

CRM verdict: BISH, **unconditionally**. Every step is finite arithmetic on integers and rationals: assign charges, compute integer powers of ε , multiply by $O(1)$ coefficients. No limits, convergence, or infinite processes appear anywhere. The $U(1)_{\text{FN}}$ symmetry need not be exact—an approximate symmetry produces an approximate hierarchy—so no LPO enters even through the symmetry itself.

Compression. With free $O(1)$ coefficients: 13 observables from 9 charges $+1$ (ε) $+13$ coefficients $= 23$ inputs. The model *reorganizes* rather than compresses. With texture zeros ($c_{ij} = 1$): $13 \rightarrow 10$ (9 charges $+ \varepsilon$). This is genuine compression, and the entire Yukawa sector is determined by a finite string of integers plus one rational number.

CRM observation. FN is the *generic* BISH explanation of any hierarchy: factor a set of numbers into powers of a base (geometric structure) times residual noise ($O(1)$ coefficients). The question CRM cannot answer is whether this factoring has physical content or is curve-fitting.

A.2 Discrete Flavor Symmetries

Discrete flavor symmetry models Altarelli and Feruglio [2010] postulate a finite group G (typically A_4 , S_4 , $\Delta(27)$, or another subgroup of $SU(3)_{\text{flavor}}$) under which the three generations transform as a triplet. The group’s representation theory constrains the Yukawa matrix structure: which entries are zero, which are related by Clebsch–Gordan coefficients. Flavon fields break G to residual subgroups in the charged-lepton and neutrino sectors.

CRM verdict: BISH. Every component is decidable finite algebra:

- Group theory of G ($|A_4| = 12$; character table and Clebsch–Gordan coefficients are finite): BISH.
- Flavon potential minimization (polynomial in finitely many variables; critical points found by solving algebraic equations): BISH.
- Yukawa matrix from group constraints (finite matrix multiplication): BISH.

No LPO enters unless G is embedded in a continuous group and the exact continuous symmetry is invoked—but the discrete group itself suffices, and its representation theory is decidable without reference to any continuous group. The embedding is scaffolding.

Compression. Typical models: ~ 15 – 20 real parameters (flavon VEVs, potential couplings, messenger scales) to produce 20 observables (13 Yukawa-sector + 7 neutrino). Compression ratio barely exceeds 1 . The symmetry constrains the *structure* of the Yukawa matrix (which entries vanish, which are related) but not the *scale*—the flavon VEVs carry the scale information and are unexplained inputs.

A.3 Randall–Sundrum / Extra Dimensions

In the Randall–Sundrum framework Randall and Sundrum [1999], one warped extra dimension of finite size πR produces the mass hierarchy through fermion localization. SM fermions are five-dimensional fields with bulk mass parameters c_i . Their zero-mode profiles scale as $f_i(y) \sim e^{(1/2 - c_i)ky}$, and the four-dimensional effective Yukawa coupling is the overlap integral of two fermion profiles with the Higgs on the IR brane:

$$y_{ij}^{(4D)} \sim y_{ij}^{(5D)} e^{-(c_i + c_j - 1)k\pi R}. \quad (10)$$

For $c_i > 1/2$, the zero mode is UV-brane-localized and its overlap with the Higgs is exponentially suppressed. An $O(1)$ spread in the bulk masses c_i produces an exponential hierarchy in the Yukawa couplings.

CRM verdict: BISH for the mechanism; LPO enters only through modulus stabilization. The five-dimensional metric (ODE with constant coefficients), the fermion zero modes (explicit exponentials), the overlap integral (closed-form), and the effective Yukawa coupling (finite arithmetic) are all BISH. The extra dimension has finite size—no limit is taken.

LPO enters through the Goldberger–Wise mechanism Goldberger and Wise [1999] for stabilizing the extra-dimensional modulus: asserting that the scalar potential has an *exact* minimum is an LPO statement. But approximate stabilization (the potential is bounded and has a region below its boundary values) is BISH and suffices for all predictions. The LPO is dispensable.

Compression. Anarchic scenario (universal 5D Yukawa): 9 bulk masses + 1 coupling + 2 geometry = 12 inputs $\rightarrow 13$ observables. General case: up to ~ 20 inputs. The exponential amplification of mild input spread is the most “efficient” mechanism in terms of output hierarchy per input parameter.

CRM observation. Randall–Sundrum is the geometric implementation of Froggatt–Nielsen. Both produce $y \sim \varepsilon^n$; in FN the base ε is the flavon VEV ratio, in RS the effective base is $e^{-(c-1/2)k\pi R}$ with the bulk mass in the exponent. The BISH content is identical—powers of a small number. The geometric language adds physical content (a dynamical mechanism for the small number) but not logical content.

A.4 String Compactification

In Type IIB string theory compactified on a Calabi–Yau threefold X , the Yukawa couplings are determined by the geometry of X : intersection numbers, period integrals, and moduli VEVs. The physical Yukawa coupling between fermions at brane intersections is schematically

$$y_{ijk} = \int_{\Sigma} \Psi_i \wedge \Psi_j \wedge \Phi_k, \quad (11)$$

where Σ is an internal cycle, Ψ_i are zero-mode wavefunctions, and Φ_k is the Higgs wavefunction. The integral depends on the complex-structure and Kähler moduli, which must be stabilized by fluxes and non-perturbative effects Bousso and Polchinski [2000].

CRM verdict: BISH to finite precision; LPO enters through moduli stabilization and the exact non-perturbative superpotential. The topological data specifying X (Hodge numbers, intersection numbers) are finite integers—BISH. Constructing X as an algebraic variety (checking that defining polynomials yield a smooth manifold) is finite algebra—BISH. Period integrals satisfy Picard–Fuchs differential equations with algebraic coefficients and can be evaluated to any finite precision—BISH.

LPO enters at two points:

1. **Moduli stabilization:** asserting that the flux superpotential $W = \int_X G_3 \wedge \Omega$ produces an *exact* minimum of the scalar potential (a function of ~ 100 complex variables) is LPO. Approximate minimization is BISH and suffices.
2. **Non-perturbative exactness:** the superpotential $W_{\text{np}} \sim e^{-aT}$ is the leading term in an instanton expansion. The claim that this form is exact to all orders is a completed-infinite statement—LPO. Truncation to finitely many instanton orders is BISH.

Both LPO components are dispensable: approximate stabilization and finite-order instanton expansion suffice for predictions at any finite precision.

Compression. In principle: 0 continuous free parameters—everything is determined by discrete choices (Calabi–Yau topology, flux integers, brane configuration). In practice: ~ 500 discrete parameters (flux integers alone number $\sim 2h^{2,1} + 2$) to produce 13 observables. The “compression” replaces 13 continuous parameters with ~ 500 discrete ones. Whether discrete inputs count as “more explained” than continuous ones is a question CRM can pose precisely but cannot answer.

A.5 Grand Unification

SU(5) Georgi and Glashow [1974] predicts $y_b = y_\tau$ at the GUT scale ($\sim 2 \times 10^{16}$ GeV) because the down-type quarks and charged leptons sit in the same **5** representation. SO(10) predicts third-generation unification $y_t = y_b = y_\tau$. The predicted GUT-scale relations, combined with RG running to the electroweak scale, yield testable predictions for mass ratios.

CRM verdict: BISH for Yukawa predictions; LPO enters through exact gauge coupling unification. The group theory of SU(5) and SO(10) (finite-dimensional Lie algebras, decidable representation theory) is BISH. The GUT-scale matching conditions ($y_b = y_\tau$) are algebraic—BISH. The RG running from GUT to electroweak scale is the finite discrete computation studied in the main text.

LPO enters through gauge coupling unification: the assertion that three running couplings $g_1(\mu)$, $g_2(\mu)$, $g_3(\mu)$ meet at *exactly* a single scale M_{GUT} . This requires deciding whether three real-valued functions are simultaneously equal—an LPO statement. The empirical content is that the couplings come *close* to meeting within experimental error bars at $\sim 2 \times 10^{16}$ GeV. Approximate unification within measurement precision is BISH.

Compression. Maximal for the third generation: 1 Yukawa \rightarrow 3 masses (in SO(10)). For lighter generations, GUT relations fail without additional structure (Georgi–Jarlskog factors). Total: 13 \rightarrow 5–7, the best compression among approaches that make testable predictions.

CRM observation. This is the one point in the audit where the scaffolding principle produces a non-trivial insight. Exact gauge coupling unification is LPO scaffolding. The empirical content (approximate unification) is BISH. The exactness assumption constrains the GUT model space: it requires specific threshold corrections from SUSY partners, specific higher-dimensional operators, and specific proton decay rates. Removing the exactness requirement—asking only for unification within experimental precision at some finite number of loop orders—admits a wider class of models. This is a concrete instance of the scaffolding principle widening the solution space, though the consequences for the mass hierarchy specifically remain to be explored.

A.6 Synthesis

Counting convention. We adopt the following rules for Table 6. *Continuous parameters*: each real-valued free parameter counts as 1 (e.g., a flavon VEV, a bulk mass, ε). *Discrete parameters*: each independent discrete choice counts as 1 (e.g., a charge assignment, a flux integer, a topological invariant). *O(1) coefficients*: counted as free parameters unless set to a specific value by a texture rule or symmetry. *Exact symmetry assumptions*: count as 0 inputs but are flagged in the “LPO Component” column if they require all-orders or completed-infinite assertions. *Observables*: the 13 Yukawa-sector quantities (9 fermion masses, 3 CKM angles, 1 CP phase). Neutrino parameters are noted where relevant but not included in the headline count. These conventions are necessarily approximate—parameter counting in BSM models is not canonical—but they suffice for the qualitative comparisons intended here.

Approach	Core	Cont. Params	Disc. Params	LPO Component	Disp.?
SM (raw)	BISH	13	0	None	—
Froggatt–Nielsen	BISH	1 (ε)	9 charges	None	—
FN (texture zeros)	BISH	1 (ε)	9 charges	None	—
Discrete flavor	BISH	8–15	group	None	—
Randall–Sundrum	BISH	9–12	0	Modulus stab.	Yes
String compact.	BISH	0	~ 500	Moduli stab. + W_{np}	Yes
SU(5) GUT	BISH	3–5	0	Exact unification	Yes
SO(10) GUT	BISH	1–3	0	Exact unification	Yes

Table 6: Audit of ultraviolet approaches to the fermion mass hierarchy. “Core Cost” and “LPO Component” are CRM-specific findings. “Cont. Params” and “Disc. Params” are standard parameter counts included for context. Every approach has BISH as its core logical content; LPO enters only through dispensable idealizations.

Three observations emerge from the audit. The first and third are specific to CRM; the second uses standard model-comparison methodology included for completeness.

- 1. Every UV approach has BISH as its core (CRM-specific).** The LPO, where it appears, enters through idealizations—exact stabilization, exact gauge unification, exact non-perturbative expansions—and is dispensable in every case. Combined with the numerical results of Sections 4 and 5, this means the fermion mass problem is entirely a problem within BISH,

at both the infrared and ultraviolet levels. No omniscience principle is needed to state, derive, or verify any proposed explanation of the mass hierarchy. This finding requires the BISH/LPO distinction to formulate and is non-trivial: it could have been otherwise (Sumino’s all-orders cancellation mechanism for the Koide formula comes close to requiring LPO essentially). The flavor problem is a different kind of mystery from those CRM was designed to illuminate, where LPO enters through completed limits and its dispensability is the finding.

2. Approaches differ in compression ratio and input character (standard methodology). Table 6 also records two quantities from standard model-comparison analysis: the *compression ratio* (observables per input parameter) and the *input character* (continuous vs. discrete). These do not depend on the CRM framework—physicists routinely count parameters without reference to constructive mathematics—but they provide useful context for the logical audit.

The compression ratio ranges from <1 (Froggatt–Nielsen with free $O(1)$ coefficients: more inputs than observables) to ~ 2.5 ($SO(10)$ for the third generation). The input character varies: Froggatt–Nielsen and discrete flavor symmetries use continuous parameters (flavon VEVs); string compactification uses purely discrete parameters (flux integers, topological data); GUTs use a mixture.

CRM sees no logical distinction between continuous and discrete inputs evaluated to finite precision—both are BISH. The question of whether discrete inputs are “more explained” than continuous ones is a question about explanatory depth, not logical cost, and lies outside CRM’s scope.

3. Exact gauge coupling unification is LPO scaffolding (CRM-specific). The scaffolding principle failed for the SM infrared (ten investigations, all negative). Applied to the ultraviolet, it identifies exact gauge coupling unification as LPO scaffolding whose removal widens the viable GUT model space. The empirical evidence for grand unification is approximate unification (BISH): three couplings come close to meeting within experimental error bars at $\sim 2 \times 10^{16}$ GeV. The assertion that they meet *exactly* is a completed-infinite statement (LPO): it requires deciding equality of three real numbers. Models achieving approximate unification without exact unification are BISH-sufficient and conventionally excluded only because the exactness assumption is treated as a theoretical requirement rather than an idealization.

This is a concrete instance of the scaffolding principle producing a non-trivial observation—not solving the mass problem, but clarifying which aspects of GUT phenomenology are empirically grounded (BISH) and which are idealizations (LPO). Whether the wider BISH-sufficient model space contains new explanations of the full mass hierarchy remains open.

The overall picture: CRM maps the logical geography of UV flavor physics with precision, and the map reveals that the terrain is uniformly BISH. The interesting LPO boundaries found in five other domains (Papers 8, 13, 14, 15, 17) do not appear here. The one exception—exact gauge coupling unification—is not about the mass hierarchy per se, but about the GUT framework within which mass predictions are made. CRM’s contribution to the flavor problem is diagnostic and taxonomic: it can tell you the logical cost of any proposed explanation, identify which idealizations are dispensable, and flag where the scaffolding principle has purchase. It cannot replace experiment.