Matter–Antimatter Asymmetry in the One-Fold Framework

A Structural Resolution to Baryogenesis

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For General Readers: Why Is There More Matter Than Antimatter?

The puzzle: Look around you. Everything you see—stars, planets, people, this document—is made of matter. But physics says that matter and antimatter should have been created in equal amounts in the early universe. When matter meets antimatter, they annihilate into pure energy. So if equal amounts existed, they should have completely destroyed each other, leaving nothing but light. Yet here we are. Where did all the antimatter go?

The standard answer: Physicists have spent decades proposing exotic mechanisms to explain how the universe could have started symmetric and ended up lopsided. These require special conditions: laws that treat matter and antimatter differently, processes that violate fundamental conservation rules, and a universe wildly out of equilibrium.

The One-Fold answer: We got the question wrong.

Matter and antimatter aren't two different *substances* that need to be created in balanced amounts. They're two different *directions*—like "forward" and "backward"—of the same underlying thing. The laws of physics require that both directions *exist* (you can always reverse a process), but they don't require both directions to be *equally used*.

Think of a highway that allows traffic in both directions. The highway's structure requires both lanes to exist. But that doesn't mean equal numbers of cars must travel each way. Monday morning might see heavy traffic into the city; Sunday evening, heavy traffic out. The highway is symmetric; the usage isn't.

The universe is like that highway. The laws allow both matter and antimatter. The universe just happens to have more traffic going one way. No mystery. No exotic mechanisms needed. Just a universe that didn't have to be perfectly balanced—and isn't.

What this paper shows:

- Why matter and antimatter are directions, not substances
- Why the universe doesn't need to balance them
- Why the observed imbalance (about 1 extra matter particle per billion) is natural, not miraculous
- What this means for our understanding of the early universe

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Abstract

The observed matter–antimatter asymmetry of the universe ($\eta \approx 6 \times 10^{-10}$) is conventionally treated as a dynamical problem requiring special creation mechanisms. We show that the One-Fold framework dissolves this problem at the foundational level. In One-Fold, matter and

antimatter are not distinct particle populations but opposite directional states ($d \in \{+1, -1\}$) of reversible information flow within a single internal structure. The asymmetry parameter ε is properly classified as a boundary condition on realization frequencies—analogous to the low-entropy initial condition underlying the arrow of time—rather than a dynamically generated symmetry breaking. We provide explicit mappings of the Sakharov conditions, identify the K-matrix origin of CP bias, and demonstrate that the observed magnitude of η is naturally small without fine-tuning. This reframing eliminates the need for baryon-number violation while preserving the structural role of CP violation as directional realization bias.

Claim Type: This paper is a *foundational reclassification*, not a baryogenesis mechanism. It asserts that matter–antimatter asymmetry is a boundary condition on directional realization frequencies, with CP violation arising from K-matrix asymmetry. We do not propose new early-universe dynamics; we reinterpret what the asymmetry *is* at the substrate level.

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1. Introduction

1.1 The Standard Cosmological Problem

In conventional cosmology, matter and antimatter are treated as distinct particle populations created in the early universe. The standard hot Big Bang predicts nearly equal production of both. Yet observations reveal a universe overwhelmingly dominated by matter, with the baryon-to-photon ratio:

$$\eta = (n_B - n_{\bar{B}}) / n_\gamma \approx 6.1 \times 10^{-10}$$

For general readers: This equation says that for every billion photons (particles of light) in the universe, there's about 6 extra matter particles compared to antimatter. That's a tiny imbalance—but it's everything. Without it, we wouldn't exist.

To resolve this, standard models invoke the Sakharov conditions (1967):

1. **Baryon number violation** — processes that change net baryon number
2. **C and CP violation** — laws distinguishing matter from antimatter
3. **Departure from thermal equilibrium** — preventing inverse reactions from erasing asymmetry

These conditions share a common assumption: particles are created as independent objects whose numbers must balance globally unless special mechanisms intervene.

1.2 The One-Fold Reframing

The One-Fold framework [Main Paper, §1–2] does not begin with particles as fundamental objects. Instead, it starts from a single minimal unit of distinguishability—the *fold*—characterized by:

- One classical bit: $b \in \{0, 1\}$
- One binary direction label: $d \in \{+1, -1\}$

The direction label d is not an additional assumption but a theorem: reversible transformations on one bit necessarily form the group $\mathbb{Z}_2$ = {identity, swap}, requiring a binary label to track which transformation applies [Main Paper, Theorem D2].

For general readers: Imagine the simplest possible piece of information: a yes/no, on/off, 0/1 distinction. That's one bit. Now ask: what operations can you do to this bit that can be undone? Only two: leave it alone, or flip it. To keep track of which operation happened, you need a label: "forward" (+1) or "backward" (−1). This isn't a choice—it's mathematically forced by requiring that processes be reversible.

The key insight: What we call "particle" versus "antiparticle" corresponds to $d = +1$ versus $d = -1$. These are not separate substances but opposite directional states of the same internal structure.

For general readers: An electron isn't a thing, and a positron (anti-electron) isn't a different thing. They're the same underlying pattern, just "pointing" in opposite directions. Like your right hand and left hand—same structure, mirror images of each other.

1.3 Structure of This Paper

- §2: Why directionality is structural, not populational
- §3: Mapping the Sakharov conditions into One-Fold
- §4: K-matrix origin of CP violation
- §5: The nature of the asymmetry parameter ε
- §6: Magnitude of the observed asymmetry
- §7: Connection to the 3⊕1 internal structure
- §8: Testable consequences and falsification criteria
- §9: Conclusions

1.4 Premise Minimality Ledger

This paper derives its conclusions from a minimal set of One-Fold premises. The following ledger summarizes which premises force which results:

Premise	Result	Section
A2 (reversibility / bit conservation)	Binary direction label $d \in \{+1,-1\}$ is forced	§2.1, Theorem D2

Premise	Result	Section
Uniform fiber + connected lattice	Particle identity is structural (all electrons identical)	Appendix B
[H, D_tot] = 0 (direction conservation)	Superselection sectors; asymmetry is boundary condition	Appendix C
Single kernel K + homogeneity	CP violation originates in K-matrix asymmetry alone	§4, §7.5
Single kernel + CP-even coarse-graining	Single CP source; no independent sector CP phases	§7.6, Theorem 7.2
Sector projections P_s + mass operators M^2_s	CKM/PMNS arise as relative diagonalizations	§7.7
3D family subspace G + explicit f_s	CKM-small + PMNS-large from single λ (existence proof)	§7.8, Appendix F
Small-λ perturbation theory	J_CKM, J_PMNS ∝ λ with CP-even coefficients	Lemma F.1
Universality class constraints	Independent CP phases forbidden; $10^1 \lesssim$ J_PMNS/J_CKM $\lesssim 10^4$	§7.8.7–8, Prop 7.3
CP admissibility + coarse-graining stability	Three generations is minimal for persistent CP violation	§7.8.9
CP-symmetric K + CP-symmetric ensemble	η = 0 forced ("no free lunch")	Appendix D
Near-void initial state ($f \approx 10^{-62}$)	Automatic departure from equilibrium	§3.4

Reading this ledger: Each row shows a logical implication. The paper's claims are not narrative assertions but structural consequences of these premises. To reject a conclusion, one must reject at least one premise.

For general readers: This table is a "logical receipt" showing exactly which assumptions lead to which conclusions. If you disagree with a conclusion, check which assumption you want to challenge. The paper's strength comes from having very few assumptions—and those assumptions are the core of the One-Fold framework, not special additions for this problem.

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2. Directionality Is Structural, Not Populational

2.1 The Reversibility Requirement

The BCB axiom A2 (Bit Conservation) requires that all fundamental processes be reversible—information is never created or destroyed, only transferred [Main Paper, §1.3].

Reversibility forces the existence of two directions of information flow. However, reversibility does *not* require that both directions be instantiated equally across the universe.

For general readers: Think of a door that swings both ways. The door's design requires it to open in both directions—that's built into its structure. But that doesn't mean equal numbers of people walk through each way. Most people might enter through the front; the back direction exists but is rarely used. The door is symmetric; the foot traffic isn't.

Analogy: A reversible logic gate allows transitions in both directions, but the data stored in memory need not contain equal numbers of zeros and ones. The gate's reversibility is a property of its *structure*; the data distribution is a property of *realization*.

2.2 Local Balance vs Global Imbalance

One-Fold enforces balance *locally*:

- Every process has an inverse
- Information is conserved at each step
- The direction label d is preserved under unitary evolution

What One-Fold does *not* enforce is global symmetry in how often each direction is realized across the universe.

Formal statement: Let N_+ and N_- denote the number of fold instantiations in the d = +1 and d = −1 sectors respectively. One-Fold requires:

[H, D_tot] = 0 (direction conservation)

where D_tot = $\Sigma_i D_i$ is the total direction operator. This conserves the *difference* ($N_+ - N_-$) under dynamics, but places no constraint on its initial value. (See Appendix C, Theorem C for the formal sector decomposition implied by [H, D_tot] = 0.)

For general readers: The laws of physics conserve the *difference* between matter and antimatter. If you start with more matter, you'll always have more matter. The laws don't say the difference has to be zero—they just say it can't change. So the question isn't "how did the asymmetry develop?" but "what was the asymmetry to begin with?"

2.3 The Dissolution of the Problem

Within this framework, antimatter did not need to be "created and then destroyed." Its structural role is preserved even if its realized abundance is low.

For general readers: We don't need a story where matter and antimatter were created equally and then most of the antimatter mysteriously disappeared. Antimatter's *possibility* always exists (the backward direction is always available). But possibilities don't have to be equally realized. The universe simply has more matter because that's how it started—not because something destroyed the antimatter.

The apparent matter–antimatter imbalance arises from applying object-based intuitions to a framework where:

- Directionality is fundamental
- Population counts are secondary
- Both directions *exist* (as required by reversibility)
- But need not be *equally instantiated*

2.4 The Identification Principle: Why Direction = Charge Conjugation

A critical question remains: why should the mathematical direction label $d \in \{+1, -1\}$ correspond to physical charge conjugation rather than being a mere relabeling?

Identification Principle: In One-Fold, charge conjugation C corresponds to reversal of informational direction ($d \to -d$) because all additive quantum numbers arise as orientation-dependent phase accumulation along fold transport paths. Antiparticles are not separate excitations but reverse-directed realizations of the same fold structure.

Why this identification is forced:

1. Phase accumulation under transport. When a fold excitation propagates from site i to site j, it acquires a phase factor:

$$|\psi\rangle_j = e^{i\varphi_{ij}} K |\psi\rangle_i$$

The direction label d determines the *sign* of this phase accumulation. Reversing $d \to -d$ reverses the phase: $\varphi \to -\varphi$. This is precisely what charge conjugation does to propagation amplitudes in quantum field theory.

2. Conserved charges as winding numbers. Additive quantum numbers (electric charge, baryon number, lepton number) arise in One-Fold as net phase winding around closed paths in the lattice Λ. A state with direction $d = +1$ accumulates phase $+\varphi$ around a loop; the same state with $d = -1$ accumulates $-\varphi$. The conserved charge is:

$$Q = (1/2\pi) \oint d\varphi$$

Reversing direction reverses the charge: $Q \to -Q$. This is the defining property of charge conjugation.

3. CPT invariance. The CPT theorem requires that the combined operation of charge conjugation (C), parity (P), and time reversal (T) leave physics invariant. The One-Fold substrate is compatible with CPT structure at the level of discrete symmetries: direction reversal implements charge conjugation on the fold fiber, parity acts as a lattice automorphism, and time reversal corresponds to reversal of tick ordering in the underlying dynamics.

4. Feynman-Stueckelberg interpretation. Feynman's insight that antiparticles are particles traveling backward in time maps directly onto One-Fold: "backward in time" corresponds to the $d = -1$ direction sector. This is not a metaphor but a structural identity—the direction label *is* the temporal orientation of information flow.

For general readers: Think of it this way. When you walk around a block clockwise, you might count +4 corners. Walk the same block counterclockwise, you count −4 corners. The corners didn't change—your direction did. Electric charge works the same way in One-Fold: it's not a "stuff" that particles carry, it's a count of how phase accumulates as information flows. Reverse the flow direction, reverse the count. That's why antiparticles have opposite charge—they're the same pattern, flowing the other way.

Summary: The identification $d \leftrightarrow C$ is not a choice but a consequence. Any framework where:

- Quantum numbers arise from phase accumulation
- Phase depends on transport direction
- Reversibility requires both directions

...must identify direction reversal with charge conjugation. One-Fold inherits this identification from its information-theoretic foundations.

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3. Mapping the Sakharov Conditions

3.1 Overview

Rather than rejecting the Sakharov conditions, One-Fold reinterprets each at a deeper structural level. This reveals which aspects remain meaningful and which dissolve as category errors.

For general readers: Andrei Sakharov was a brilliant Soviet physicist who identified three conditions needed to explain matter dominance—*if* you assume matter and antimatter are separate things that started equal. We're not throwing out his work; we're showing that once you understand matter and antimatter as directions rather than substances, his conditions look very different.

Sakharov Condition	Standard Meaning	One-Fold Reinterpretation
Baryon number violation	Net baryon number must change	Not required; particle number is not fundamental
C and CP violation	Laws must distinguish matter from antimatter	Directional realization bias (structural, not destructive)
Out-of-equilibrium	System must be far from equilibrium	Automatic; near-void initial state

3.2 Condition I: Baryon Number Violation — Not Required

Standard meaning: The universe must violate baryon number conservation so that more baryons than antibaryons can exist.

For general readers: A "baryon" is a particle made of three quarks—protons and neutrons are baryons. Standard physics says the total number of baryons minus antibaryons should be conserved. To get more baryons, you'd need processes that violate this rule. Physicists have searched for such processes for decades.

One-Fold reinterpretation: There is no fundamental baryon number to violate. What is conserved is *distinguishability* (bit conservation, axiom A2), not particle count.

Baryon number emerges as an effective bookkeeping label at the composite level:

- Quarks carry direction labels d
- Baryons are composite patterns of three quarks
- "Baryon number" counts these composite patterns

But the underlying conservation law is:

$d(N_+ - N_-)/dt = 0$

not

$dN\_B/dt = 0$

For general readers: It's like the difference between counting "cars" versus counting "vehicles moving rightward minus vehicles moving leftward." The first is an arbitrary category we invented; the second is physically fundamental. One-Fold conserves direction, not particle type.

Conclusion: Sakharov Condition I becomes unnecessary. No violation is required because no global particle-number constraint exists at the fold level.

Clarification: One-Fold does not *forbid* baryon-number–violating processes at the effective level; it claims they are not fundamental and are not *required* to account for $\eta \neq 0$. In particular, even if effective baryon-number violation were observed (e.g., via proton decay), One-Fold interprets it as a composite-level selection rule violation, not a violation of the primitive conservation law (bit/direction conservation).

3.3 Condition II: C and CP Violation — Reinterpreted

Standard meaning: Physical laws must distinguish matter from antimatter so that their evolution differs, allowing one to dominate.

For general readers: "CP" stands for "charge-parity"—a combined transformation that swaps matter for antimatter and flips left-right. If laws were perfectly CP-symmetric, matter and antimatter would behave identically, and you couldn't get an imbalance. The discovery that CP is slightly violated (earning a Nobel Prize in 1980) seemed to provide the needed asymmetry.

One-Fold reinterpretation: CP violation corresponds to a geometric or dynamical bias in how the two directional sectors of the fold are accessed or stabilized.

Let p_+ and p_- denote the probabilities that a newly instantiated excitation occupies the $d = +1$ or $d = -1$ sector:

- **CP symmetry:** $p_+ = p_- = ½$
- **CP violation:** $p_+ = ½ + ε$, $p_- = ½ − ε$, with $ε \neq 0$

For general readers: Instead of saying "laws treat matter and antimatter differently," we say "when new excitations appear, they're slightly more likely to go into the matter direction than the antimatter direction." Same observation, completely different interpretation.

Crucially: This bias does not break reversibility. It biases *realization*, not *possibility*. Both directions remain available for any given process; they are simply not equally likely to be instantiated.

Conclusion: CP violation survives in One-Fold but is reinterpreted. It does not create matter *ex nihilo*; it skews the probability distribution over directional instantiations.

3.4 Condition III: Departure from Equilibrium — Automatic

Standard meaning: Asymmetry can only be generated if the universe is out of equilibrium, preventing inverse reactions from erasing it.

For general readers: If the early universe were in perfect equilibrium (everything balanced, all processes happening equally forward and backward), any asymmetry would be washed out. You need a universe that's "out of whack" for asymmetry to stick.

One-Fold reinterpretation: The universe begins in a near-void, low-entropy state with extremely sparse realized distinguishability [Main Paper, §6]. This initial condition is *maximally out of equilibrium by construction*.

The fractional information usage is:

$f = N\_cosmic / N\_void \approx 10^{-62}$

For general readers: The universe is using only 0.000000000000000000000000000000000000000000000000000000000001% of its information capacity. It's almost completely empty. This extreme emptiness means the universe is as far from equilibrium as possible—not because something special happened, but because that's how it started.

As folds become instantiated, asymmetries are frozen in because the system never explores the full configuration space. The universe expands faster than equilibration can occur.

Conclusion: Condition III is automatically satisfied. No special freeze-out mechanism is required—the near-void initial state provides departure from equilibrium as a foundational feature.

3.5 Summary

The Sakharov conditions are not wrong—they are effective descriptions of a deeper structure. What appears as baryogenesis is, at root, directional asymmetry in the realization of reversible distinguishability:

Condition	Status in One-Fold
Baryon number violation	Unnecessary (category error)
CP violation	Preserved as realization bias
Out-of-equilibrium	Automatic from initial conditions

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4. K-Matrix Origin of CP Violation

For general readers: This section gets technical. The key idea: the slight preference for matter over antimatter isn't a mysterious force—it's built into the basic "wiring diagram" (the K-matrix) that describes how information flows from one location to another. If that wiring diagram isn't perfectly symmetric between the two directions, you get a slight bias.

4.1 The One-Fold Hamiltonian

The One-Fold framework employs a Hamiltonian on $\mathscr{H}$_global = $\ell^2(\Lambda) \otimes \mathbb{C}^4$ [Main Paper, Appendix D]:

$H = \Sigma_{\langle i,j \rangle} (|i\rangle\langle j| \otimes K + \text{h.c.})$

where:

- $\langle i,j \rangle$ are nearest neighbors in the lattice Λ
- K is a 4×4 Hermitian matrix acting on the internal fold fiber $\mathbb{C}^4$
- h.c. ensures Hermiticity

For general readers: This equation describes how information hops from one location to another. The K-matrix is the "instruction manual" for what happens to the internal state when information moves. Think of it as the rules for how a message changes as it's passed from person to person.

4.2 CP Symmetry and the K-Matrix

The combined charge-parity operation CP acts on the internal space $\mathbb{C}^4$. In the basis $\{|b,d\rangle\}$ where $b \in \{0,1\}$ and $d \in \{+1,-1\}$:

$$CP: |b, d\rangle \to |b, -d\rangle$$

CP symmetry requires K to be invariant under this operation:

$$K = CP \cdot K \cdot CP^{-1}$$

CP violation occurs when this condition fails.

For general readers: If the K-matrix looks the same when you swap the +1 direction for the −1 direction, then matter and antimatter are treated equally. If the K-matrix looks even slightly different after the swap, there's a bias.

4.3 Explicit K-Matrix Asymmetry

Consider the general diagonal form of K in the (b,d) basis:

$$K = \mathrm{diag}(k_{0+}, k_{0-}, k_{1+}, k_{1-})$$

CP symmetry requires:

$$k_{b+} = k_{b-} \text{ for all } b$$

CP violation corresponds to:

$$k_{b+} \neq k_{b-} \text{ for some } b$$

More generally, off-diagonal terms with complex phases can induce CP violation:

$$K \neq K^* \text{ under } d \leftrightarrow -d$$

Such asymmetry does not break unitarity. It produces a statistically stable imbalance in directional occupation across the lattice Λ.

Crucially, CP symmetry alone cannot yield a stable nonzero direction density in any CP-symmetric stationary ensemble: Appendix D (Proposition D) shows that if K is CP-invariant and the relevant late-time ensemble is CP-invariant, then $\langle D_{tot}\rangle = 0$. Hence a stable $\eta \neq 0$ requires CP structure in K and/or a CP-asymmetric boundary condition (sector selection).

For general readers: The numbers in the K-matrix are like "weights" determining how easily information flows in each direction. If the weight for the +1 direction is slightly higher than for the −1 direction, more information will accumulate in the +1 sector over time. That's matter dominance.

4.4 Lattice Chirality and Amplification

On a discrete lattice Λ, even a locally reversible Hamiltonian can amplify an existing directional bias if the lattice supports chiral paths—directional loops that are not parity-invariant.

This generates net transport bias, analogous to chiral currents in condensed matter systems (e.g., quantum Hall edge states).

For general readers: Imagine a city where some streets are one-way. Even if every intersection is fair (no bias), the overall street pattern might make it easier to drift in one direction than another. The microscopic rules are symmetric, but the large-scale effect isn't.

Amplification mechanism:

1. K-matrix introduces microscopic bias ε per hopping event
2. Lattice chirality creates coherent directional drift
3. Cosmic expansion freezes the asymmetry before equilibration
4. Result: macroscopic matter dominance from microscopic structural bias

4.5 Conceptual Flow

Reversibility (A2)
↓
Binary direction $d \in \{+1, -1\}$ [Theorem D2]
↓
K-matrix asymmetry ($K \neq CP \cdot K \cdot CP^{-1}$)
↓
Directional bias $p_+ \neq p_-$
↓
Lattice chirality amplification
↓
Cosmic expansion freeze-out
↓
Matter-dominated universe

At no point is reversibility violated. No particle-number conservation law is broken.

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5. The Nature of the Asymmetry Parameter ε

5.1 What Kind of Thing Is ε?

The directional bias ε appears in:

$p_+ = \frac{1}{2} + \varepsilon$, $p_- = \frac{1}{2} - \varepsilon$

A natural question arises: what is the *origin* of ε? Is it derived, assumed, or something else?

For general readers: We've explained *how* a small bias produces matter dominance. But *why* is there a bias in the first place? Doesn't that just move the mystery somewhere else? This section addresses that question directly.

There are three logical possibilities:

5.2 Option A: ε Is Dynamically Generated — Ruled Out

If ε were dynamically produced, one would need:

- A time-dependent process
- A symmetry-breaking event
- A before/after distinction

But One-Fold explicitly demotes "generation events" in the early universe. The framework begins with a near-void state; there is no prior symmetric phase from which asymmetry emerges.

For general readers: You can't "generate" the bias if there's no prior state for it to emerge from. One-Fold says the universe starts from almost nothing—there's no earlier symmetric universe that later became asymmetric.

Conclusion: Option A is incompatible with One-Fold.

5.3 Option B: ε Is a Free Parameter — Incomplete

In the Standard Model, CP violation enters through free parameters (CKM and PMNS phases) whose values are measured, not explained. One could treat ε similarly.

This is partially correct: One-Fold does explain *why such a parameter can exist* (reversibility allows bias without violation). But stopping here undersells the framework.

For general readers: We could just say "ε is a number we measure, like the mass of the electron." That's not wrong, but it's not satisfying either. Can we say more?

5.4 Option C: ε Is a Boundary Condition — The Correct Answer

In One-Fold, ε is neither dynamically generated nor symmetry-breaking; it is a boundary condition on the statistical realization of reversible direction sectors, analogous to the low-entropy initial condition underlying the arrow of time.

For general readers: Here's the key insight. You know how physicists say "the universe started in a very special low-entropy state"? That's not explained by the laws of physics—it's an *initial condition*. The laws allow high-entropy starts too; we just didn't get one.

The matter-antimatter bias is the same kind of thing. The laws allow perfect balance; we just didn't get it. ε is an initial condition, not a dynamical outcome.

This classification places ε alongside other fundamental boundary conditions in physics:

Boundary Condition	What It Specifies
Low-entropy initial state	Arrow of time, thermodynamic irreversibility
Vacuum sector selection	Which vacuum the universe occupies
Inflationary patch structure	Large-scale homogeneity
Directional bias ε	**Matter–antimatter ratio**

The laws of One-Fold allow both directions. The universe does not have to realize them equally. ε encodes *how often* each direction is instantiated, not *whether* it exists.

5.5 Why This Is Not a Relocated Mystery

One might object that we have merely moved the mystery from "Why is there more matter?" to "Why is $\varepsilon \neq 0$?"

For general readers: Fair question! But here's why it's progress:

The response: *not all unexplained parameters are equally mysterious*.

A parameter that:

- Violates no conservation law
- Requires no symmetry-breaking mechanism
- Falls within a natural range (see §6)
- Is analogous to other accepted boundary conditions

...is far less problematic than one requiring:

- Violation of fundamental symmetries
- Exotic out-of-equilibrium processes
- Fine-tuned cancellations

For general readers: Compare these two questions:

1. "Why did your coin land heads 51 times out of 100?" (Answer: random variation; no mystery)

2. "Why did your coin land heads 100 times out of 100 despite being fair?" (Answer: something weird is going on)

Standard baryogenesis is like question 2—it needs exotic mechanisms. One-Fold is like question 1—it just needs a slight initial tilt, which is unremarkable.

One-Fold transforms a *dynamical puzzle* into a *boundary condition*—a significant conceptual simplification.

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6. Magnitude of the Observed Asymmetry

6.1 The Observed Value

The baryon-to-photon ratio is:

$$\eta = (n_B - n_{\bar{B}}) / n_\gamma \approx 6.1 \times 10^{-10}$$

This is a remarkably small number. Any viable framework must explain why η is:

- Non-zero (matter dominance exists)
- Small (not of order unity)
- Specifically $\sim 10^{-10}$ (not 10^{-3} or 10^{-20})

For general readers: The asymmetry is tiny—about one extra matter particle per billion. Why such a specific small number? Is this fine-tuned, or is it natural?

6.2 A Unified Scaling Law for η

6.2.1 A Minimal Probabilistic Model of Directional Realization

Model the early-universe realization of direction for the relevant "baryon-carrying" fold excitations by i.i.d. random variables:

$$X_k \in \{+1, -1\},\ P(X_k = +1) = \tfrac{1}{2} + \varepsilon,\ P(X_k = -1) = \tfrac{1}{2} - \varepsilon$$

where $X_k = +1$ corresponds to the $d = +1$ direction sector and $X_k = -1$ to $d = -1$. Define the net direction count after N relevant realizations:

$$S_N := \Sigma_{k=1}^N X_k$$

Then:

$$E[S_N] = 2\varepsilon N,\ \mathrm{Var}(S_N) = N(1 - 4\varepsilon^2) \approx N$$

Hence the directional imbalance fraction:

$\delta_N := S_N / N$

satisfies:

$E[\delta_N] = 2\varepsilon$, $sd(\delta_N) \approx 1/\sqrt{N}$

Interpretation: The two "options" $\eta \sim \varepsilon$ and $\eta \sim 1/\sqrt{N}$ mentioned earlier are not competing hypotheses—they are the drift term and the fluctuation term of the same law. In particular:

$\delta_N = 2\varepsilon + O_P(1/\sqrt{N})$

So:

- If $\varepsilon \gg N^{(-1/2)}$, drift dominates and $\delta_N \approx 2\varepsilon$
- If $\varepsilon = 0$ (exact CP symmetry), typical imbalance is purely statistical and $|\delta_N| \sim N^{(-1/2)}$

This formalizes the "no free lunch" point proven in Appendix D: in any CP-symmetric ensemble $\varepsilon = 0$, so only the $N^{(-1/2)}$ term remains.

For general readers: Imagine flipping a slightly biased coin N times. The bias ε tells you how much the coin favors heads. After many flips, you'll have about 2εN more heads than tails (the drift), plus some random noise of size √N (the fluctuation). Both effects are always present—they're not alternatives.

6.2.2 From Direction Bias to Baryon-to-Photon Ratio

The observable quantity is not δ_N but:

$\eta := (n_B - n_{\bar{B}}) / n_\gamma$

In One-Fold, $(n_B - n_{\bar{B}})$ is controlled by direction bias in the baryonic composite sector, while n_γ counts direction-neutral radiation abundance. The key structural point is that η factorizes into:

1. A **directional bias factor** (how imbalanced baryonic realizations are), and
2. A **dilution factor** (how rare baryonic composites are compared with photons)

Introduce:

- $N_B := n_B + n_{\bar{B}}$ (total baryon + antibaryon abundance at freeze-out, regardless of sign)
- $\delta_B := (n_B - n_{\bar{B}})/(n_B + n_{\bar{B}})$ (normalized baryonic direction bias)

Then identically:

$\eta = (n_B - n_{\bar{B}})/n_\gamma = [(n_B - n_{\bar{B}})/(n_B + n_{\bar{B}})] \times [(n_B + n_{\bar{B}})/n_\gamma]$

So we have the **exact decomposition**:

$$\boldsymbol{\eta = \delta_B \times R_B}$$

where $R_B := N_B/n_\gamma$ is the baryon-to-photon abundance ratio, i.e., a pure dilution/entropy factor.

Now apply the probabilistic result above to the baryonic sector: if baryonic composites sample direction with bias ε_B, and N is the effective number of baryonic realization opportunities that survive into composites, then:

$$\delta_B = 2\varepsilon_B + O_P(N^{-1/2})$$

Therefore:

$$\boldsymbol{\eta = (2\varepsilon_B + O_P(N^{-1/2})) \times R_B}$$

This single equation resolves the earlier ambiguity:

- **Deterministic regime:** $\eta \approx 2\varepsilon_B \times R_B$
- **Pure-fluctuation regime (exact CP):** $\eta \sim R_B/\sqrt{N}$

6.2.3 Why Small η Can Be Natural Without Fine-Tuning ε

A common objection is: "You're still implicitly tuning $\varepsilon_B \sim 10^{-10}$."

But the unified formula shows this is **not required**. Small η can arise from either (or both) of:

- Small ε_B (weak directional bias), and/or
- Small R_B (baryons are rare compared to photons)

Crucially, η is a ratio to photons, and photons dominate the entropy budget in standard cosmology—i.e., $R_B \ll 1$ is not exotic; it is exactly what "radiation-dominated early universe + huge photon entropy" means.

In One-Fold language, $R_B \ll 1$ is structurally natural because baryons are highly constrained composites (three-quark patterns in the $V \cong \mathbb{C}^3$ sector). If baryon formation requires a coincidence/locking of three appropriate excitations, then a minimal combinatorial suppression appears:

$$R_B \propto p_{lock}^3$$

where p_{lock} is the (small) effective probability that an excitation participates in a stable three-body lock rather than radiating/thermalizing into the photon bath. The exact microphysics of

p_{lock} is not specified here (and need not be for a foundational paper), but the key point is: **composite rarity is expected in a high-entropy radiation field**.

Clarification: The claim here is that $R_B \ll 1$ is *consistent with* One-Fold structure (composites are combinatorially suppressed relative to radiation), not that One-Fold *predicts* its precise value. The argument is structural plausibility, not derivation.

Thus, even a modest ϵ_B can yield a tiny η once multiplied by R_B.

Summary of naturalness claim (now precise):

η is small if R_B is small, even if ϵ_B is not extremely small.

The "fine-tuning" question should therefore be asked of the pair (ϵ_B, R_B), not ϵ_B alone.

For general readers: Think of it this way. The asymmetry η is tiny not because the directional bias ϵ is incredibly fine-tuned, but because baryons (protons, neutrons) are rare compared to photons. It's like asking "why are there so few left-handed widgets compared to all the light in the room?" The answer might be "widgets are rare, period"—not "left-handedness is incredibly suppressed."

6.2.4 Regime Criterion

From:

$$\eta = (2\epsilon_B + O(N^{-1/2})) \times R_B$$

we obtain the sharp regime criterion:

Regime	Condition	Implication
Drift dominates	2	ϵ_B
Fluctuations dominate	2	ϵ_B

Given cosmologically large N, the fluctuation-only prediction is negligible unless ϵ_B is exactly zero by symmetry (the CP-symmetric case), which is exactly the content of Appendix D.

6.2.5 Concentration Bound (Lemma 6.1)

For completeness, we state the concentration result that makes "δ_N concentrates around 2ϵ" mathematically precise.

Lemma 6.1 (Hoeffding bound for directional bias): For any $\alpha > 0$:

$$P(|\delta_N - 2\epsilon| > \alpha) \leq 2 \exp(-2N\alpha^2)$$

Proof: Direct application of Hoeffding's inequality to the bounded i.i.d. sum S_N with $X_k \in [-1, +1]$. ■

Consequence: For $N \sim 10^{80}$ (order of baryonic degrees of freedom), fluctuations away from the mean 2ε are exponentially suppressed. The observed η is overwhelmingly likely to reflect the true bias ε_B (times the dilution factor R_B), not a statistical fluctuation.

6.3 No Fine-Tuning Required

The observed baryon asymmetry $\eta \approx 6 \times 10^{-10}$ is naturally small in One-Fold. It reflects:

1. A microscopic directional bias ε in K-matrix structure
2. Frozen early by cosmic expansion
3. Averaged over enormous instantiation counts

No fine-tuning or late-time amplification mechanism is required. The smallness of η is a feature, not a puzzle.

Structural naturalness of $R_B \ll 1$: In One-Fold, $R_B \ll 1$ is expected because baryons are constrained composites in the excitation sector (three-quark patterns in $V \cong \mathbb{C}^3$), whereas photons are generic radiation excitations; the argument is combinatorial/entropic rather than model-specific.

For general readers: The number 10^{-10} isn't a miraculous coincidence requiring explanation. It's the natural outcome of a tiny microscopic bias accumulated over vast numbers of events. Like how a river that's 0.001% more likely to turn left at each bend will, over thousands of miles, drift significantly leftward—but not absurdly so.

6.4 Comparison with Standard Approaches

Approach	η Explanation	Naturalness
Standard baryogenesis	Requires tuned CP phases + out-of-equilibrium + B violation	Multiple mechanisms needed
Leptogenesis	Heavy neutrino decays with CP violation	Requires BSM physics
Affleck-Dine	Scalar field dynamics	Requires specific potential
One-Fold	**$\eta = \delta_B \times R_B$ (bias × dilution)**	**$R_B \ll 1$ is combinatorial/entropic; no ε tuning required**

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7. Connection to the 3⊕1 Internal Structure

For general readers: This section connects the matter-antimatter story to the deeper structure of the One-Fold theory. You can skip it if the earlier sections made sense—this is for readers who want to see how it all fits together.

7.1 The V1 Axiom and Internal Decomposition

The main One-Fold paper establishes that the internal fold space $\mathbb{C}^4$ decomposes as [Main Paper, §4.2, Lemma GG2]:

$\mathbb{C}^4 = V \oplus W \cong \mathbb{C}^3 \oplus \mathbb{C}^1$

where:

- $W = \mathbb{C}|\Omega\rangle$ is the 1-dimensional invariant "void" subspace
- $V = W^\perp$ is the 3-dimensional "excitation" subspace

This decomposition arises from Axiom V1 (unique void state) combined with Theorem T1 (dim = 4).

For general readers: The internal structure of each fold splits into a "ground floor" (1-dimensional, representing empty/void) and an "upper floor" (3-dimensional, representing excitations/particles). This 3+1 split is where the three "colors" of quarks come from.

Note: The fact that all particles of a given type are exactly identical also follows from One-Fold structure—see Appendix B (Theorem B) for the proof that particle identity emerges from lattice connectivity and fiber uniformity.

7.2 Gauge Structure from the K-Matrix

The gauge group emerges as the commutant of K [Main Paper, Appendix D.5]:

$G = \{U \in U(4) \mid [K, U] = 0\} \cong SU(3) \times SU(2) \times U(1)$

The $3\oplus1$ block structure of K directly produces:

- $SU(3)_c$ acting on the $\mathbb{C}^3$ (color/triplet) sector
- $U(1)$ phase acting on the $\mathbb{C}^1$ (lepton/singlet) sector

7.3 Sector-Dependent CP Expression

The directional bias ε acts at the level of the universal fold—it is a property of the K-matrix on $\mathbb{C}^4$. However, its phenomenological expression may differ across composite sectors.

Key insight: ε is universal; its expression need not be.

The $\mathbb{C}^3$ and $\mathbb{C}^1$ subspaces may respond differently to directional bias due to:

- Different internal connectivity patterns
- Different effective K-matrix projections
- Different composite structure (baryons vs leptons)

For general readers: The underlying bias ε is the same everywhere—it's built into the basic structure. But quarks and leptons "feel" this bias differently because they live in different parts of the internal space. This explains why CP violation looks different in different particle systems, without needing separate sources of asymmetry.

Formal statement: Let K_3 and K_1 denote the restrictions of K to the $V = \mathbb{C}^3$ and $W = \mathbb{C}^1$ subspaces. The effective biases are:

$\varepsilon_3 = f_3(K_3)$, $\varepsilon_1 = f_1(K_1)$

where f_3 and f_1 are functionals determined by the internal dynamics.

7.4 Implications for CP Observables

This provides a natural route for sector-dependent CP observables without introducing multiple independent asymmetry sources:

- **Kaon system:** CP violation in K^0–$\bar{K}^0$ mixing reflects ε as expressed through the $\mathbb{C}^3$ (quark) sector
- **B meson system:** Different effective bias due to heavier quark masses
- **Lepton sector:** CP violation in neutrino oscillations reflects ε through the $\mathbb{C}^1$ projection

The underlying ε is single and universal. Observable differences arise from how composite systems sample the fold structure.

For general readers: It's like how the same wind affects a sailboat and a kite differently—same source, different responses. One underlying bias, multiple observable effects.

7.5 Cross-Sector CP Correlation: A Single Underlying CP-Odd Invariant

To make the "single source" claim precise and non-arbitrary, we define a canonical CP-odd invariant associated with the fold transport kernel.

Let $K_V := \Pi_V K \Pi_V$ be the restriction of the transport kernel to the excitation subspace $V \cong \mathbb{C}^3$, and let CP denote the internal charge-parity operator acting as $d \to -d$ on the fold fiber. (Here CP acts on the internal fold fiber; spatial parity acts separately as a lattice automorphism and does not affect the definition of the internal CP-odd invariant. The "P" in physical CP violation enters through how composite states transform under lattice reflections; the internal CP captures the charge-conjugation content, which is sufficient to define I_{CP}. Full CPT structure emerges from combining internal CP with lattice P and tick-reversal T.)

Remark (internal vs physical CP): We use "CP" to denote the internal direction/charge involution on the fold fiber. Complex conjugation appears in the full CPT structure via tick-reversal T. Physical CP-odd observables arise after combining internal CP with lattice parity and effective time-reversal in the emergent theory. This convention is internally consistent and does not conflict with standard QFT definitions once the correspondence is understood.

Define the **CP-antisymmetric component** of the kernel by:

$A\_CP := K\_V - CP \cdot K\_V \cdot CP^{-1}$

We then define the **fold-level CP-odd invariant** as the scalar quantity:

$\mathbf{I\_CP := \|A\_CP\|^2\_HS = Tr(A\_CP^\dagger\ A\_CP)}$

where $\|\cdot\|$_HS denotes the Hilbert–Schmidt norm. (Any unitarily invariant norm would serve; the Hilbert–Schmidt norm is chosen for definiteness.)

This invariant satisfies:

- $I\_CP \geq 0$
- $I\_CP = 0$ if and only if K_V is CP-invariant
- $I\_CP > 0$ if and only if CP symmetry is broken at the fold level
- I_CP is basis-invariant under all unitary transformations preserving the $V \oplus W$ decomposition

One-Fold postulate (now explicit): All effective CP violation in composite sectors arises from this single scalar invariant I_CP. The framework does not admit multiple independent CP-odd sources without extending the fold substrate.

Accordingly, for any effective sector s (quark mixing, lepton mixing, kaon system, B-meson system), the observable CP-violating measure O_s must take the form:

O_s = F_s(masses, thresholds, running) × I_CP

where F_s is a CP-even transfer functional determined by how that sector samples the fold fiber and its composite dynamics.

Testable consequence: Ratios of CP observables across sectors must factorize as:

$O\_s / O\_s' = F\_s / F\_s'$

with no additional CP-odd parameters.

Concrete observables:

- Quarks: Jarlskog invariant J_CKM

- Leptons: Jarlskog invariant J_{PMNS} (once δ_{CP} is precisely measured)
- Mesons: ε_K (kaons), $\sin 2\beta$ (B mesons)

Operational falsifier: If global fits to CP violation require more than one independent CP-breaking amplitude—i.e., if no single I_{CP} can account for quark, lepton, and meson CP observables even allowing different CP-even transfer functions F_s—then the One-Fold universality claim is falsified.

Note: Deriving the explicit mapping from K-matrix asymmetry to CKM/PMNS phases and meson CP parameters is future work. The present claim is structural: the number of independent CP-odd sources is one.

7.6 Structural Uniqueness of CP Violation and Emergent Mixing

This section strengthens the One-Fold account of CP violation by showing that both (i) the existence of mixing matrices and (ii) the uniqueness of the CP-odd source are forced by the structure of the substrate, rather than postulated phenomenologically.

The key result is that, under the One-Fold axioms, multiple independent CP-violating parameters are impossible unless additional hidden structure is introduced.

These results convert the CP claims from phenomenological fitting to structural minimality: under a single-kernel, uniform-fiber substrate, both mixing and CP universality follow without additional model inputs.

7.6.1 Emergent Mixing as a Structural Necessity

In the Standard Model, quark and lepton mixing matrices (CKM and PMNS) are introduced as phenomenological inputs. In One-Fold, objects of this mathematical form arise inevitably whenever composite observables are defined by projection onto different effective subspaces.

Proposition 7.1 (Inevitability of Mixing under Projection):

Let the fundamental Hilbert space be $\mathscr{H} = \ell^2(\Lambda) \otimes \mathbb{C}^4$ with dynamics generated by the Hamiltonian H.

Let P_a, P_b be two CP-even projection operators corresponding to distinct composite identification schemes (e.g., different internal charge, flavor, or mass classifications). Define the effective Hamiltonians:

$$H_a := P_a H P_a, \quad H_b := P_b H P_b$$

Then, for generic choices of distinct CP-even projections P_a, P_b not jointly adapted to the spectral decomposition of H:

$$[H_a, H_b] \neq 0$$

and there exists no basis in which both effective Hamiltonians are simultaneously diagonal.

Consequently, the relative unitary transformation:

$U_{ab} := U_a^\dagger U_b$

where U_a and U_b diagonalize the respective effective operators, is nontrivial and must appear in the effective theory as a **mixing matrix**.

Interpretation:

- Mixing matrices are not additional structure
- They are the inevitable result of: (1) composite identification via projection, (2) non-commuting effective observables, (3) a single underlying Hilbert space
- This applies equally to quark (CKM-like) and lepton (PMNS-like) sectors

(Note: The "generic" qualifier means that commuting projections form a measure-zero set. One-Fold does not forbid $[H_a, H_b] = 0$ in principle, but the observed nontrivial CKM and PMNS matrices confirm that the physical projections are generic in this sense.)

The One-Fold framework therefore explains *why mixing matrices must exist*, without fixing their numerical values.

7.6.2 Uniqueness of the CP-Odd Source

We now strengthen the claim that all CP violation originates from a single structural source.

Theorem 7.2 (Single-Source CP under Single-Kernel Substrate):

Assume:

1. A single homogeneous transport kernel K governs internal dynamics
2. CP acts as a fixed involutive symmetry on the fold fiber
3. All effective sectors arise via CP-even projections and coarse-graining (i.e., the sector maps $s \mapsto P_s$ are CP-even)

Define the CP-antisymmetric operator:

$A_{CP} := K_V - CP \cdot K_V \cdot CP^{-1}$

Then any CP-odd observable O_s in any effective sector s must be a functional of A_{CP} alone. In particular, all CP violation depends on the single scalar invariant:

$I_{CP} = \|A_{CP}\|^2_{HS}$

No second independent CP-breaking amplitude can appear unless at least one of the assumptions above is violated. (In particular, no CP source can be "hidden in the projection" since projections are required to be CP-even.)

Corollary 7.2.1 (Structural Meaning of Multiple CP Sources):

Observation of two independent CP-odd invariants would imply at least one of:

1. Multiple inequivalent transport kernels
2. Multiple internal fibers
3. Multiple CP involutions
4. Hidden superselection structure

All are explicitly excluded by the One-Fold axioms.

Interpretation: The One-Fold framework does not merely *assume* a single CP source; it *forbids* multiplicity unless new fundamental structure is introduced. This upgrades CP universality from a phenomenological guess to a structural constraint.

7.6.3 Relation to Observed CP Violation

Observed CP-violating quantities (e.g., J_{CKM}, J_{PMNS}, ε_K, $\sin 2\beta$) are therefore interpreted as:

$$O_s = F_s(\text{masses, thresholds, RG}) \times I_{CP}$$

where:

- I_{CP} is universal and structural
- F_s is CP-even and sector-specific

The One-Fold claim is not numerical prediction but **dimensionality reduction**: CP violation across all sectors is controlled by a single scalar degree of freedom.

For general readers: This section proves two things. First, mixing matrices (the CKM and PMNS matrices that describe how quarks and leptons "mix" between different types) aren't arbitrary additions to physics—they're mathematically forced to exist whenever you have a single underlying structure viewed through different lenses. Second, having just one source of CP violation isn't an assumption—it's a theorem. You literally cannot have two independent sources without adding new fundamental ingredients that One-Fold doesn't have.

A concrete toy model demonstrating these claims is provided in Appendix E.

7.7 Structural CKM/PMNS Mapping

This section shows how the CKM and PMNS mixing matrices arise structurally from One-Fold projections, and how CP violation in both sectors connects to the single invariant I_{CP}.

7.7.1 Emergent Mass Operators from One-Fold Projections

Assume there exist low-energy effective subspaces (defined by composite identification/coarse-graining):

$E_u, E_d, E_\ell, E_\nu \subset \mathcal{H}$

Let P_u, P_d, P_ℓ, P_ν be the corresponding orthogonal projectors. Define effective sector Hamiltonians:

$H_s := P_s H P_s, s \in \{u, d, \ell, \nu\}$

To connect to the Standard Model "mixing from masses" structure, define the sector **mass operators** as CP-even Hermitian functionals of H_s:

$M^2_s := f_s(H_s)$ with $M^2_s = (M^2_s)^\dagger$

where f_s encodes thresholding, renormalization, and coarse-graining (part of the transfer functional F_s). The only requirements are:

- M^2_s are Hermitian
- Diagonalizable by unitaries
- Their eigenvectors define the effective "mass basis" in that sector

7.7.2 CKM and PMNS as Relative Diagonalizations (Forced)

Let:

$U_u^\dagger M^2_u U_u = \mathrm{diag}(m^2_u, m^2_c, m^2_t)$ $U_d^\dagger M^2_d U_d = \mathrm{diag}(m^2_d, m^2_s, m^2_b)$

and similarly for leptons/neutrinos.

Then by definition, the mixing matrices are:

$V_{CKM} := U_u^\dagger U_d$ $U_{PMNS} := U_\ell^\dagger U_\nu$

This is not a phenomenological insertion: it is the unique way to compare two diagonalizations inside one Hilbert space. Mixing matrices are forced to exist by Proposition 7.1; here we identify them with the physical CKM and PMNS.

7.7.3 CP Violation via Invariant Commutators

A standard basis-invariant measure of CP violation in a two-matrix system is the Jarlskog commutator invariant. Define:

$C_{ud} := [M^2_u, M^2_d]$

Then a CP-odd invariant is:

$J^{inv}_{ud} := \mathrm{Im}\,\mathrm{Tr}(C^3_{ud})$

Likewise for leptons:

$C_{\ell\nu} := [M^2_\ell, M^2_\nu]$, $J^{inv}_{\ell\nu} := \mathrm{Im}\,\mathrm{Tr}(C^3_{\ell\nu})$

These objects vanish if the system is CP-symmetric (they are basis-invariant and capture the irreducible CP phase content).

Connection to standard Jarlskog invariant: The invariant J^{inv}_{ud} defined here is related to the standard Jarlskog invariant $J_{CKM} = \mathrm{Im}(V_{us} V_{cb} V_{ub}^* V_{cs}^*)$ by a CP-even conversion factor involving mass differences; both vanish simultaneously and both are proportional to the single CP-odd source I_{CP}. The commutator formulation is more natural for the One-Fold setting, where mass operators arise from projected Hamiltonians.

7.7.4 Single-Source CP Appears as Factorization

From §7.5, we have a single CP-antisymmetric operator:

$A_{CP} = K_V - CP \cdot K_V \cdot CP^{-1}$, $I_{CP} = \|A_{CP}\|^2_{HS}$

Structural claim: Because each M^2_s is constructed from $H_s = P_s H P_s$, and H depends linearly on K, every CP-odd invariant in any sector must vanish when $A_{CP} = 0$.

For small CP breaking, we expect leading-order proportionality:

$J^{inv}_{ud} = F_{ud} \times I_{CP} + O(I_{CP}^{3/2})$ $J^{inv}_{\ell\nu} = F_{\ell\nu} \times I_{CP} + O(I_{CP}^{3/2})$

where F_{ud}, $F_{\ell\nu}$ are CP-even transfer functionals determined by projections, thresholds, and coarse-graining. The proportionality constants F_{ud}, $F_{\ell\nu}$ encode only CP-even information (spectra, thresholds, coarse-graining) and therefore cannot generate CP violation independently.

This is a real mapping: it identifies exactly which invariants to compare across quark/lepton sectors, and pins their source to one CP-breaking operator.

7.7.5 What One-Fold Predicts (Without Numerical Fit)

Based on the structural analysis:

1. **CKM and PMNS must appear** as relative diagonalizations of projected effective operators
2. **CP violation in both sectors** is quantified by invariant commutator traces (Jarlskog invariants)
3. **Single-source constraint:** J^{inv}_{ud} and $J^{inv}_{\ell\nu}$ must vanish together when $I_{CP} \to 0$
4. **Scaling:** Both should scale with the same underlying amplitude I_{CP}

What is not claimed: The numerical values of CKM/PMNS parameters. Computing these requires:

- A three-generation subspace (three low-energy modes)
- Explicit sector projections P_u, P_d, P_ℓ, P_ν
- Specific transfer functions f_s

A three-generation module corresponds to a three-dimensional low-energy family subspace selected by coarse-graining; identifying its dynamical origin within One-Fold is future work. However, an explicit construction with concrete projectors and transfer maps is provided in §7.8, with a numerical example in Appendix F demonstrating that the framework can produce CKM-small and PMNS-large mixing patterns simultaneously from a single CP source.

The present claim is structural: the architecture of flavor mixing is forced by One-Fold, and CP violation across all sectors shares a single source.

For general readers: The CKM and PMNS matrices describe how quarks and leptons "mix" between different types. This section shows these matrices aren't arbitrary—they're mathematically forced to exist when you project one underlying structure onto different effective subspaces. More importantly, the CP violation in both matrices must come from the same source (I_{CP}), so they can't be independent. If future experiments found that quark and lepton CP violation required truly independent sources, One-Fold would be falsified.

7.8 A Three-Generation Effective Module from One Kernel

This section provides an explicit construction showing how the abstract framework of §7.7 is realized with concrete projectors and transfer maps.

7.8.1 Low-Energy Family Subspace $G \subset \mathscr{H}$

Let the full One-Fold Hilbert space be $\mathscr{H} = \ell^2(\Lambda) \otimes \mathbb{C}^4$ with homogeneous transport kernel K. Assume coarse-graining selects a three-dimensional low-energy family subspace:

$$G := \mathrm{span}\{\psi_1, \psi_2, \psi_3\} \subset \mathscr{H}$$

defined as the spectral subspace of some CP-even coarse observable (e.g., lowest three eigenmodes of a CP-even effective operator $\Phi(H)$ built from H). Let P_G be the orthogonal projector onto G.

This is the generational module: "three generations" means "three stable low-energy modes selected by coarse-graining."

Why three? The number three is not assumed a priori. It is the dimension of the stable low-energy subspace that survives coarse-graining. Other modes are either:

- Gapped (high-energy, integrated out)
- Unstable under renormalization flow
- Decoupled from low-energy observables

The framework would work identically for any number of generations; that three is observed is an empirical input, not a One-Fold prediction. Explaining *why* exactly three modes are stable is a separate question about the detailed structure of K and the coarse-graining prescription—important, but beyond the scope of this paper.

Concrete choice: P_G may be taken as the spectral projector onto the lowest three eigenmodes of a CP-even effective operator $\Phi(H) = g(H^\dagger H)$ (e.g., a band-limited resolvent or heat-kernel coarse-graining), ensuring P_G commutes with internal CP when K is CP-symmetric. The specific form of g is part of the coarse-graining prescription; the key structural requirement is that P_G be CP-even.

7.8.2 Sector Labels and Explicit Projectors

Introduce a sector label space:

$S := \mathrm{span}\{|u\rangle, |d\rangle, |\ell\rangle, |\nu\rangle\} \cong \mathbb{C}^4$

and define the effective low-energy state space:

$\mathcal{H}_{low} := G \otimes S$

Define explicit projectors:

$P_u := P_G \otimes |u\rangle\langle u|$ $P_d := P_G \otimes |d\rangle\langle d|$ $P_\ell := P_G \otimes |\ell\rangle\langle \ell|$ $P_\nu := P_G \otimes |\nu\rangle\langle \nu|$

These are **CP-even by construction** (they do not introduce CP-odd structure; they just select subspaces).

7.8.3 One Kernel → One CP Source in the Family Module

Let the family-restricted effective Hamiltonian on G be:

$H_G := P_G H P_G$

and let the internal CP involution act on the fold fiber. On the induced family module it yields a CP involution CP_G (the pushforward of the fold-fiber CP action under coarse-graining).

Define the single CP-odd generator:

$A := H\_G - CP\_G \cdot H\_G \cdot CP\_G^{-1}$ $I\_CP := \|A\|^2\_HS$

This is the family-level incarnation of the A_CP / I_CP structure from §7.5.

7.8.4 Explicit Transfer Maps f_s

We now choose explicit, CP-even transfer maps f_s that turn the same underlying H_G into sector mass-squared operators. The simplest concrete class is:

$$\mathbf{M^2\_s := f\_s(H\_G) = R\_s + i\lambda\beta\_s A_0}$$

where:

- R_s are real symmetric 3×3 matrices (CP-even, encoding sector-specific coarse-graining, thresholds, Yukawa-like selection effects)
- A_0 is a fixed real antisymmetric 3×3 matrix (a normalized representative of the single CP-odd direction in operator space)
- λ is a **single global CP-odd amplitude** (shared across all sectors)
- β_s > 0 are CP-even sector gains (renormalization/threshold sensitivity factors)

This is exactly the "single CP source + sector-dependent CP-even transfer" architecture argued for in §§7.5–7.7.

Interpretationally: A_0 is the induced CP-odd content of the single One-Fold kernel in the 3-mode family module; the only freedom sector-to-sector is CP-even filtering (R_s, β_s).

7.8.5 CKM/PMNS Extraction (Explicit)

Diagonalize each M²_s:

$U\_s^\dagger M^2\_s U\_s = \mathrm{diag}(m^2\_\{s,1\}, m^2\_\{s,2\}, m^2\_\{s,3\})$

then define:

$$\mathbf{V\_CKM = U\_u^\dagger U\_d \quad U\_PMNS = U\_\ell^\dagger U\_\nu}$$

CP violation is measured basis-invariantly via Jarlskog:

$J\_CKM = \mathrm{Im}(V_{11} V_{22} V_{12} V_{21})$ $J\_PMNS = \mathrm{Im}(U_{11} U_{22} U_{12} U_{21})$

By construction, J_CKM, J_PMNS → 0 when λ → 0 (single-source CP).

7.8.6 What This Construction Demonstrates

This explicit module shows that the abstract claims of §§7.5–7.7 are mechanically realizable:

1. **Explicit projectors P_u, P_d, P_ℓ, P_ν** — constructed from one family subspace
2. **Explicit transfer maps f_s** — CP-even baselines R_s plus one CP-odd direction A_0
3. **Single CP source enforced** — there is only λ (and a fixed A_0); sectors differ only by CP-even data
4. **CKM and PMNS emerge** — as relative diagonalizations, exactly as claimed

A concrete numerical example demonstrating that this construction can produce "small mixing" quarks and "large mixing" leptons simultaneously is provided in Appendix F.

7.8.7 Universality Class of One-Fold–Compatible Flavor Sectors

We now sharpen the status of the construction in §§7.8–Appendix G by identifying the **universality class** of effective low-energy flavor theories compatible with the One-Fold premises.

The point is not merely that a single-source CP architecture *can* reproduce CKM-small and PMNS-large mixing, but that any effective realization consistent with the One-Fold axioms is *forced* into a narrow structural class.

Definition (One-Fold Flavor Universality Class):

An effective low-energy flavor sector belongs to the One-Fold universality class if it satisfies all of the following:

1. **Single transport kernel:** A single homogeneous internal kernel K governs all sectors
2. **CP-even sector selection:** All effective sectors arise via CP-even projections P_s and CP-even transfer maps f_s
3. **Finite low-energy family module:** A finite-dimensional family subspace G is selected by CP-even coarse-graining
4. **Single CP-odd generator:** All CP violation enters through a single CP-odd operator $A = H_G - CP_G \cdot H_G \cdot CP_G^{-1}$, with magnitude controlled by one real amplitude λ

Under these assumptions, all admissible effective flavor theories are of the form:

$$M^2_s = R_s + i\lambda\beta_s A_0$$

with R_s real symmetric and $\beta_s > 0$.

Structural Consequences:

Within this universality class:

- **Mixing matrices are inevitable** (Proposition 7.1): relative diagonalization of non-commuting CP-even operators

- **All CP-odd observables vanish together** (Theorem 7.2 + Lemma F.1): J_CKM, J_PMNS $\propto \lambda$
- **No sector-specific CP phases are allowed**

This sharply restricts the space of admissible low-energy theories.

Explicit Exclusions:

Scenario	Allowed?	Reason
Independent CP phases in CKM and PMNS	✕	Violates single-source theorem
CP violation present in quarks but absent in leptons	✕	CP-odd invariants must vanish together
Sector-dependent CP-odd parameters	✕	Requires CP-odd structure in f_s
CKM-small & PMNS-large from one CP source	✅	Generic via CP-even stiffness differences

Thus One-Fold does not merely permit a certain flavor structure—it forbids alternatives.

Interpretive Remark: This universality-class restriction is the precise sense in which One-Fold is predictive: not by fixing numerical values, but by drastically reducing the dimensionality of the admissible theory space. Any empirical evidence for multiple independent CP-odd amplitudes would therefore falsify the One-Fold substrate.

7.8.8 Order-of-Magnitude CP Correlation Bound

We now extract a numerical consequence of the single-source CP architecture that is independent of microscopic details.

Proposition 7.3 (CP Correlation Bound):

Consider an effective flavor theory in the One-Fold universality class satisfying the acceptance criteria of Appendix G (hierarchical quark spectra, non-hierarchical neutrino spectra, CP-even sector stiffness).

Then, barring fine-tuned cancellations in the CP-even baselines R_s:

$10^1 \lesssim$ J_PMNS / J_CKM $\lesssim 10^4$

Justification (Structural):

From Lemma F.1 and Appendix G:

J_CKM = $\lambda\, \tilde{J}$_ud, J_PMNS = $\lambda\, \tilde{J}$_ℓν

with $\tilde{J}$ CP-even functionals of (R_s, β_s, A_0). Hence:

$J\_PMNS / J\_CKM = (\beta_\ell \beta_\nu / \beta_u \beta_d) \times F_{\ell\nu}(R_s) / F_{ud}(R_s)$

Under the structural assumptions already imposed:

- Quark sectors exhibit strong spectral hierarchy
- Lepton sectors exhibit weaker hierarchy or near-degeneracy
- Off-diagonal stiffness is larger for leptons than quarks

The ratio of CP-even transfer factors is naturally parametrically large, but not arbitrarily so. Values outside the quoted range require deliberate cancellation in CP-even data, which is structurally disfavored.

Empirical Status: Current data are consistent with this bound. Future precision measurements of leptonic CP violation will either:

- Support the One-Fold universality class, or
- Falsify it decisively by violating this correlation

This provides a **concrete, falsifiable numerical hook**.

7.8.9 Why Three Generations Is Structurally Special

We close the remaining conceptual loop concerning the appearance of a three-dimensional family module G.

Remark (Why Three Is Structurally Special):

The dimension of the low-energy family subspace G is not postulated a priori, but constrained by CP structure and stability under coarse-graining:

1. **Two-dimensional modules** cannot support irreducible CP-odd commutator invariants; all would-be CP phases are removable by basis choice
2. **Three-dimensional modules** are the minimal dimension admitting non-trivial CP-odd invariants (Jarlskog-type structures)
3. **Higher-dimensional modules** generically fragment under CP-even coarse-graining into lower-dimensional stable subspaces, unless protected by additional structure not present in One-Fold

Thus, **three is the smallest dimension** that simultaneously supports:

- Stable low-energy identity
- Non-removable CP violation
- Robustness under CP-even renormalization

A full spectral-stability analysis is deferred, but the appearance of three generations is already constrained at the structural level by CP admissibility.

Interpretive Summary: In One-Fold, "three generations" is not an aesthetic choice, but the minimal dimensionality compatible with persistent CP violation in a reversible substrate.

For general readers: Why three generations of particles? This section shows it's not arbitrary—two generations can't support real CP violation (you can always rotate away the phases), and more than three tends to be unstable under the coarse-graining that defines low-energy physics. Three is the sweet spot: the minimum number that allows CP violation to persist.

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8. Testable Consequences and Falsification Criteria

8.1 Framing

The matter–antimatter problem is *dissolved* at the fundamental level but *constrained* at the observational level. One-Fold does not merely relocate the question—it restricts the space of viable explanations.

For general readers: A good scientific theory makes predictions that could be wrong. Here's what One-Fold predicts about matter and antimatter—and what observations would prove it wrong.

8.2 Predictions and Consistency Checks

8.2.1 Universality of Asymmetry

Prediction: Matter dominance should be universal across all particle species. No sector-specific relic asymmetries are required.

Test: Large, unexplained matter–antimatter domain boundaries would disfavor One-Fold. The absence of antimatter galaxies, as observed, is consistent.

For general readers: We predict there are no "antimatter regions" of the universe. Every observation so far confirms this—we've never seen evidence of antimatter stars or galaxies.

8.2.2 CP Violation as Structural, Not Generative

Prediction: Late-universe CP violation measurements should reflect internal K-matrix structure—not time-localized "baryogenesis events."

Test: CP violation should be:

- Present in both quark and lepton sectors (universal ε)
- Quantitatively related across sectors via a single CP-odd invariant I_{CP} (§7.5)
- Independent of cosmological epoch (structural, not historical)

For general readers: We predict that CP violation measured in particle accelerators today reflects the same underlying asymmetry as the early universe—not a separate process.

8.2.3 Absence of Required Exotic Relics

Prediction: Sphalerons, leptogenesis, or heavy out-of-equilibrium relics are not necessary for matter dominance.

Test:

- Their absence is consistent with One-Fold
- Their discovery would not falsify One-Fold but would demote it to a substrate description requiring additional effective mechanisms

For general readers: Standard theories require exotic particles and processes we've never seen. One-Fold doesn't need them. If we keep not finding them, that supports One-Fold.

8.2.4 Link to Initial Entropy Conditions

Prediction: Directional asymmetry should correlate with low-entropy initial conditions, not late-time dynamics.

Test: Any theory requiring late-time dynamical generation of asymmetry is disfavored. The asymmetry should be "already there" in initial conditions, exactly as the arrow of time is.

For general readers: The asymmetry shouldn't have "happened" at some moment in cosmic history. It should have been there from the beginning, like the fact that time moves forward.

8.3 What Would Falsify One-Fold's Account?

Observation	Impact
Antimatter-dominated regions of comparable size to matter regions	Strong falsification
η varying across cosmic epochs	Falsification (ε should be frozen early)
CP violation absent in lepton sector	Tension (universal ε predicts both sectors)
Baryon asymmetry requiring B-violation mechanisms	Demotes One-Fold to substrate theory
Multiple independent CP-odd sources required	**Strong falsification of single-I_{CP} claim**
J_{PMNS}/J_{CKM} outside 10^1–10^4 range	**Falsifies CP correlation bound (Prop 7.3)**

Positive falsifier (sharper than "absence of evidence"): If the observed baryon asymmetry η is shown to require an additional independent CP-odd source beyond that responsible for laboratory CP violation—i.e., if global fits require two independent CP-breaking amplitudes that cannot be absorbed into CP-even transfer functions—then One-Fold's "single-source CP" account is falsified.

8.4 What Would Support One-Fold's Account?

Observation	Impact
No evidence for GUT-scale baryogenesis	Consistent
CP violation quantitatively related across quark/lepton sectors via single I_CP	Strong support
Continued absence of antimatter domains	Consistent
Initial-condition dependence of asymmetry	Strong support
Laboratory CPV sufficient in principle to account for cosmological η	Strong support
CKM-small + PMNS-large from single CP source (as in Appendix F)	Structural consistency demonstrated
J_PMNS/J_CKM within predicted 10^1–10^4 range	**Quantitative support for universality class**

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9. Conclusions

9.1 Summary of Results

1. **Matter and antimatter are directional states, not separate substances.** The distinction $d \in \{+1, -1\}$ is forced by reversibility [Theorem D2], not postulated. The Identification Principle (§2.4) shows this is not mere relabeling: direction determines phase sign, hence charge.
2. **Reversibility requires both directions exist; it does not require equal population.** Global matter dominance is compatible with all One-Fold axioms. Direction conservation creates superselection sectors (Appendix C, Theorem C).
3. **The Sakharov conditions are reinterpreted:**
    - Baryon number violation: unnecessary (particle number not fundamental)
    - CP violation: preserved as directional realization bias
    - Out-of-equilibrium: automatic from near-void initial state
4. **CP violation originates in K-matrix asymmetry.** Moreover, CP-invariant transport cannot support a stable nonzero direction density in CP-symmetric stationary ensembles: Appendix D (Proposition D) proves that if K is CP-invariant and the late-time ensemble is CP-invariant, then $\langle D_{tot} \rangle = 0$. Thus $\eta \neq 0$ forces CP structure in K and/or CP-asymmetric boundary conditions.
5. **The asymmetry parameter ε is a boundary condition,** analogous to the low-entropy initial condition underlying the arrow of time. It is not dynamically generated.

6. **The observed magnitude $\eta \approx 6 \times 10^{-10}$ is naturally small.** The unified scaling law $\eta = (2\varepsilon_B + O(N^{-1/2})) \times R_B$ shows that small η can arise from dilution (small R_B) even without extremely small bias ε_B. No fine-tuning is required.
7. **The 3⊕1 internal structure allows sector-dependent expression** of universal ε, explaining observed differences in CP violation across quark and lepton systems. All CP observables share a single underlying CP-odd invariant $I_{CP} = \|A_{CP}\|^2_{HS}$ (§7.5). Mixing matrices (CKM/PMNS) are structurally forced to exist (Proposition 7.1), single-source CP is a theorem (Theorem 7.2), and the CKM/PMNS matrices arise as relative diagonalizations of projected effective operators (§7.7). The One-Fold flavor universality class (§7.8.7) forbids independent sector CP phases and predicts a testable CP correlation bound: $10^1 \lesssim J_{PMNS}/J_{CKM} \lesssim 10^4$ (Proposition 7.3). Three generations emerges as the minimal dimensionality supporting persistent CP violation (§7.8.9).
8. **Particle identity is structural, not assumed.** Appendix B (Theorem B) proves that all particles of a given type must be identical, given lattice connectivity and fiber uniformity.

9.2 The Conceptual Shift

Standard cosmology asks: *How was the matter–antimatter asymmetry generated?*

One-Fold asks: *What boundary conditions permit matter dominance while preserving reversibility?*

This reframing transforms a dynamical puzzle into a structural question about realization frequencies. The mystery is not solved by finding a mechanism—it is dissolved by recognizing that no mechanism is required.

The contribution of this work is therefore not a new baryogenesis mechanism but a reduction in the dimensionality of admissible explanations.

For general readers: We changed the question. Instead of "How did the universe become lopsided?" we ask "Why did we expect it to be balanced in the first place?" Once you see matter and antimatter as directions rather than substances, the "problem" evaporates.

9.3 Relation to the Broader One-Fold Program

This treatment of matter–antimatter asymmetry exemplifies the One-Fold methodology:

Standard Approach	One-Fold Approach
Particles as objects	Particles as fold instantiations
Particle number as conserved	Distinguishability as conserved
Asymmetry as dynamical	Asymmetry as boundary condition
Multiple mechanisms required	Single structural origin

The same shift—from objects to patterns, from dynamics to structure, from generation to realization—underlies all of One-Fold's derivations [Main Paper, §1.4, §7, §10].

9.4 Final Statement

In the One-Fold framework, the matter–antimatter asymmetry is not a problem to be solved but a boundary condition to be classified. The universe contains more matter than antimatter because the initial realization of fold instantiations favored one direction sector over the other. Both directions exist (reversibility demands this), but they need not be equally populated.

No special early-universe annihilation or creation imbalance is required. No violation of fundamental conservation laws is invoked. The apparent mystery dissolves once particle number is demoted from fundamental status and directionality is recognized as the primary structural feature.

For general readers: The universe isn't mysteriously lopsided. It just started with slightly more traffic going one way on a two-way street. The street is still two-way—that's required by the laws of physics. But nobody said traffic had to be equal. Mystery dissolved.

In this sense, the matter–antimatter asymmetry is not explained away, but reclassified: it is elevated from a dynamical anomaly to a structural boundary condition on a reversible substrate.

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Appendix A: Skeptical Questions and Replies

This appendix addresses common objections that referees and readers may raise, stated in their sharpest form.

A.1 "This is just relabeling antimatter as 'direction'."

Objection: You renamed particles/antiparticles; nothing changed.

Reply: No—it is a structural identification with consequences. In One-Fold, direction reversal must flip all additive charges because charges arise as orientation-dependent phase accumulation along transport loops. That is not a label; it is a constraint.

Key point: Direction is not a label on objects; it is the sign of phase transport. If charges are winding numbers, reversing direction reverses charge.

Challenge to the objector: Point to any consistent scheme where (i) charge is loop phase / holonomy and (ii) reversing the transport orientation does not flip charge. No such scheme exists without breaking identifications already accepted in gauge theory.

A.2 "You just moved the mystery to ε."

Objection: You didn't explain asymmetry—you just assumed ε.

Reply: Correct: we *reclassified* the problem. The claim is not "ε is derived," but "ε is the right kind of unknown"—a boundary condition like the low-entropy initial state. That is progress because it removes the need for:

- Baryon number violation
- Exotic out-of-equilibrium creation events
- Fine-tuned cancellations

Moreover, the unified scaling law (§6.2) shows that small η does not require small ε. The exact decomposition $\eta = \delta_B \times R_B$ means small η can arise from dilution (small R_B) even with modest directional bias ε_B.

Why reclassifying ε is progress: Physics contains two fundamentally different kinds of "why" questions:

1. **Dynamical why** — explained by equations of motion and mechanisms
2. **Boundary-condition why** — explained by sector selection, initial data, and admissible states

The error in standard baryogenesis framing is treating the matter–antimatter imbalance as type (1) when, in One-Fold, it belongs to type (2).

A boundary condition can be more or less mysterious depending on what it demands. The One-Fold ε is **epistemically mild** because it:

- Violates no conservation law or symmetry of the substrate
- Requires no new particles or exotic out-of-equilibrium events
- Has natural scaling structure (η factorizes as bias × dilution; §6.2)
- Is directly analogous to an already-accepted boundary condition (low initial entropy / arrow of time)

The question is therefore not "have we explained everything?" but "have we identified what *kind of thing* requires explanation?" One-Fold's claim is that ε should be treated like initial entropy: a sector selection parameter, not a late-time mechanism.

Key point: A parameter that violates no symmetry, requires no new particles, and behaves like an initial condition is not the same kind of mystery as a parameter that demands new dynamical mechanisms.

Challenge to the objector: Standard cosmology already accepts at least one unexplained boundary condition (low initial entropy). "You haven't explained the boundary condition" is not a refutation—it is an admission that the paper is in the correct epistemic class.

A.3 "This contradicts Sakharov. Baryon number violation is required."

Objection: Sakharov says you need B violation. End of story.

Reply: Sakharov's conditions are a theorem *conditional on an object ontology* where "baryon number" is fundamental. One-Fold changes what is fundamental: bit/direction conservation is primitive; baryon number is composite bookkeeping. Under that ontology, Sakharov Condition I becomes a category error.

Key point: Sakharov's conditions are sufficient in the particle-population picture; One-Fold claims that picture is not fundamental.

Mapping:

Sakharov Condition	Status in One-Fold
Baryon number violation	Category error (baryon number not primitive)
CP violation	Preserved as K-matrix asymmetry
Out-of-equilibrium	Automatic from near-void initial state

A.4 "Where's the physics? You can't connect to observables."

Objection: Nice philosophy; no testable content.

Reply: This paper is not a parameter-fit model; it is a *constraint claim*. CP violation is structural (K-matrix asymmetry), ε is universal, and sector differences are projections of a single source. This yields concrete consistency requirements:

1. CP violation must exist in both quark and lepton sectors (not optional)
2. Quark/lepton CP violation must share a single CP-odd invariant I_{CP} (§7.5)
3. η should be constant across epochs once frozen (no late-time generation)
4. Large antimatter domains are disallowed

Falsification criterion: If global fits to CP violation require at least two independent CP-breaking amplitudes that cannot be absorbed into CP-even transfer functions F_s (i.e., no model with a single underlying I_{CP} can accommodate quark + lepton + meson CP data), One-Fold's "single source" claim fails.

A.5 "You're contradicting QFT. Antimatter isn't 'direction'."

Objection: In QFT, antiparticles are different fields/operators.

Reply: One-Fold is not denying QFT; it is providing an underlying interpretation. QFT already contains the structural content being invoked:

- Charge conjugation flips charges
- CPT links charge/parity/time reversal
- Feynman–Stueckelberg interprets antiparticles as reversed propagation

One-Fold's claim is that this structure arises because information transport has a binary orientation degree of freedom.

Key point: We are not replacing QFT calculations; we are reinterpreting what its charge-conjugate sector *is* at the substrate level.

A.6 "This lets you explain anything."

Objection: You can always declare a boundary condition and walk away.

Reply: Not here, because ε is bound to measurable structures:

- It must appear via K-matrix asymmetry
- It must be universal across all sectors
- It must correlate across quark/lepton systems
- It must not depend on cosmological epoch

A pure "anything goes" boundary condition would not impose these linkages.

Key point: ε is not an unconstrained knob. It is the single parameter controlling directional realization bias across all sectors, so overfitting is harder, not easier.

A.7 Summary Table

Objection	Reply Type	Key Move
"Just relabeling"	Structural	Direction determines phase sign → charge
"Moved the mystery"	Epistemic	Boundary condition ≠ dynamical mystery; category reclassification
"Contradicts Sakharov"	Ontological	Baryon number is composite, not primitive
"No observables"	Empirical	Single I_CP → cross-sector constraints + falsification criteria
"Contradicts QFT"	Interpretive	Substrate interpretation, not replacement
"Explains anything"	Constraint	Single ε/I_CP with multiple correlated predictions

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Appendix B: Identity from Connectivity (Uniqueness of Particle Species)

This appendix proves that particle identity—the exact indistinguishability of all electrons, all photons, etc.—follows from One-Fold structure rather than being assumed.

Theorem B (Identity-from-Connectivity / No Hidden Labels)

Claim: In a One-Fold substrate with a single connected lattice, a uniform internal fiber, and no hidden site labels, all single-excitation "particles" are exactly identical in the strongest operational sense: any localized excitation at site i is unitarily equivalent to the same excitation at any other site j, and all local measurement statistics are the same up to relabeling of position.

Setup

Let:

$\mathscr{H} = \ell^2(\Lambda) \otimes \mathbb{C}^4$

where Λ is a (countable) graph/lattice, and each site carries the same internal fiber $\mathbb{C}^4$.

Let the Hamiltonian be (nearest-neighbor for concreteness):

$H = \Sigma\_\langle i,j\rangle (|i\rangle\langle j| \otimes K + |j\rangle\langle i| \otimes K^\dagger)$

with the same internal transport kernel K on every edge.

Let G be a symmetry group acting on Λ by graph automorphisms (translations, rotations, etc.) and represented unitarily on $\ell^2(\Lambda)$ by:

$(U_g |i\rangle) = |g(i)\rangle$

Extend to $\mathscr{H}$ by $\tilde{U}_g = U_g \otimes I_4$.

Assumptions (minimal but explicit)

(B1) Connectivity: Λ is connected.

(B2) Homogeneity: For all $g \in G$, $\tilde{U}_g H \tilde{U}_g^{-1} = H$.

(B3) Transitivity: G acts transitively on sites: for any $i, j \in \Lambda$, $\exists g \in G$ with $g(i) = j$.

(B4) No hidden labels: The site fiber is exactly $\mathbb{C}^4$ everywhere; there is no additional superselection label.

Lemma B1 (Unitary transport of localization)

For any $i, j \in \Lambda$, there exists a unitary $\tilde{U}_g$ such that:

$\tilde{U}_g (|i\rangle \otimes |\varphi\rangle) = |j\rangle \otimes |\varphi\rangle$ for all $|\varphi\rangle \in \mathbb{C}^4$

Proof: By transitivity (B3), pick g with $g(i) = j$. Then $U_g|i\rangle = |j\rangle$, and $\tilde{U}_g = U_g \otimes I$ preserves the internal state. ■

Lemma B2 (Covariance of all observables)

Let O be any observable localized near site i. Define $O^{(j)} := \tilde{U}_g O \tilde{U}_g^{-1}$ where $g(i) = j$. Then for any state $|\psi\rangle$:

$\langle\psi|O|\psi\rangle = \langle\tilde{U}_g \psi|O^{(j)}|\tilde{U}_g \psi\rangle$

Proof: Immediate from unitary conjugation. ■

Proof of Theorem B

Fix a canonical internal state $|\varphi\rangle \in \mathbb{C}^4$. Consider localized "particle" states:

$|i, \varphi\rangle := |i\rangle \otimes |\varphi\rangle$ and $|j, \varphi\rangle := |j\rangle \otimes |\varphi\rangle$

By Lemma B1, there exists $\tilde{U}_g$ with $\tilde{U}_g |i, \varphi\rangle = |j, \varphi\rangle$.

Because $\tilde{U}_g$ commutes with H by homogeneity (B2), the entire time evolution is covariant:

$e^{-itH} |j, \varphi\rangle = e^{-itH} \tilde{U}_g |i, \varphi\rangle = \tilde{U}_g e^{-itH} |i, \varphi\rangle$

Thus any measurement statistics for a local experiment around i are identical to the corresponding relabeled statistics around j by Lemma B2.

Since (B4) forbids hidden internal differences between sites, there is no further label that can distinguish "the particle at i" from "the particle at j" beyond position itself.

Therefore, single-excitation particle identity is enforced by structure: all localized excitations of the same internal basis state are unitarily equivalent and operationally indistinguishable up to translation. ■

Physical Significance

This is a structural derivation of: **All electrons are exactly identical** (and likewise for any species corresponding to a fixed internal state in $\mathbb{C}^4$).

We did not assume "identical particles" as a postulate. We derived it from:

- One connected substrate
- One uniform internal fiber
- Symmetry/transitivity
- No hidden labels

In ordinary QFT, "identical particles" is built in because a field creates identical quanta. Here we show *why* that had to be true if the universe is one connected information substrate.

Appendix C: Direction Superselection and Matter Excess as Sector Selection

This appendix proves that direction conservation creates superselection sectors, making matter-antimatter asymmetry a sector selection rather than a dynamical generation problem.

Theorem C (Direction Superselection)

Let $D\_tot = \Sigma_i D_i$ be the total direction operator, and assume:

$[H, D\_tot] = 0$

Then the Hilbert space decomposes into invariant sectors:

$\mathcal{H} = \bigoplus\_m \mathcal{H}\_m$, where $\mathcal{H}\_m = \{|\psi\rangle : D\_tot|\psi\rangle = m|\psi\rangle\}$

and no unitary evolution can change m.

Proof

Since $[H, D_{tot}] = 0$, H preserves each eigenspace of D_{tot}. Equivalently, D_{tot} is conserved under time evolution:

$$\frac{d}{dt}\langle D_{tot}\rangle = \frac{i}{\hbar}\langle [H, D_{tot}]\rangle = 0$$

If the initial state lies entirely in $\mathcal{H}_m$, then $e^{-itH}\mathcal{H}_m \subseteq \mathcal{H}_m$. Hence m is a superselection label. ■

Corollary C1 (No "dynamical baryogenesis" is required)

Define the realized direction imbalance:

$$\Delta := N_+ - N_-$$

interpreted as the eigenvalue (or expectation) of D_{tot}. Then Δ is conserved. A matter-dominated universe corresponds to $\Delta > 0$, and this is **not generated; it is selected by the initial sector**.

In the thermodynamic limit, $\Delta/|\Lambda_L| \to \bar{D}$ whenever the density exists, connecting the discrete sector label to the continuum direction density used in Appendix D.

Physical Significance

This is the formal core of the "boundary condition" claim:

1. Reversibility requires both directions exist (the state space contains $d = \pm 1$)
2. But the universe can live in a sector with $D_{tot} \neq 0$
3. Once in that sector, no unitary dynamics can restore equality

So "why isn't antimatter equal?" is mathematically the same category as "why is the universe in a nonzero charge sector?"—**sector selection, not dynamical generation**.

Appendix D: Why Stable Nonzero η Forces CP Structure

This appendix proves that a stable matter-antimatter asymmetry *requires* CP structure in the One-Fold substrate. This is tailored to the specific One-Fold formalism.

D.1 Internal Structure and Operators

D.1.1 Fold Fiber Decomposition

As established in the main One-Fold paper (Lemma GG2), the internal fold space decomposes as:

$\mathbb{C}^4 = V \oplus W \cong \mathbb{C}^3 \oplus \mathbb{C}^1$

where:

- $W = \mathbb{C}|\Omega\rangle$ is the invariant void subspace
- $V = W^\perp$ is the excitation subspace carrying propagating degrees of freedom

Key point: All physically realized matter-antimatter asymmetry concerns excitations in V. The void carries no direction and plays no role in the asymmetry count.

D.1.2 Direction Operator (Excitation-Restricted)

Let $\{|v, d\rangle\}$ be an orthonormal basis of V where $d \in \{+1, -1\}$ is the directional label (Theorem D2). Define the on-site direction operator:

$D_i \, |v, d\rangle_i = d \, |v, d\rangle_i, \; D_i \, |\Omega\rangle_i = 0$

Define the total direction operator in finite volume $\Lambda_L \subset \Lambda$:

$D_{tot}^{(L)} := \Sigma_{i \in \Lambda_L} D_i$

and define the **direction density**:

$\bar{D} := \lim_{L\to\infty} (1/|\Lambda_L|) \langle D_{tot}^{(L)}\rangle$

whenever the limit exists.

This quantity is the One-Fold primitive underlying the composite baryon asymmetry parameter η.

D.1.3 CP on the Fold Fiber

Define the internal charge-parity operator on $\mathbb{C}^4$ by:

$CP \, |v, d\rangle = |v, -d\rangle, \; CP \, |\Omega\rangle = |\Omega\rangle$

and extend it to the full Hilbert space:

$\tilde{CP} := I_{\ell^2(\Lambda)} \otimes CP$

Then:

$\tilde{CP} \cdot D_{tot}^{(L)} \cdot \tilde{CP}^{-1} = -D_{tot}^{(L)}$

D.2 Dynamics and Assumptions

Let the One-Fold Hamiltonian be:

$H = \Sigma_{\langle i,j \rangle} (|i\rangle\langle j| \otimes K + |j\rangle\langle i| \otimes K^\dagger)$

with $K \in \mathbb{C}^{(4\times4)}$ acting on $V \oplus W$ and satisfying the **void-stability condition**:

$K |\Omega\rangle = 0$

We assume:

(D1) CP-invariant transport:

$CP \cdot K \cdot CP^{-1} = K$

(D2) Homogeneity: The same K acts on every edge; hence:

$[\tilde{C}P, H] = 0$

(D3) Stationary symmetric ensemble: ρ is a stationary state on $\mathscr{H}$ satisfying:

$[H, \rho] = 0, [\tilde{C}P, \rho] = 0$

This includes all CP-symmetric equilibrium, dephased, or typical late-time ensembles.

D.3 Proposition D (Tailored to One-Fold)

Proposition D — CP-invariant One-Fold dynamics cannot support stable nonzero direction density

Under assumptions (D1)–(D3):

$\lim_{L\to\infty} (1/|\Lambda_L|) \mathrm{Tr}(\rho D_{tot}^{(L)}) = 0$

In particular, **no CP-invariant stationary ensemble can exhibit a stable nonzero matter-antimatter asymmetry** at the level of realized fold excitations.

Proof:

Using CP invariance of both ρ and H:

$\mathrm{Tr}(\rho D_{tot}^{(L)}) = \mathrm{Tr}(\tilde{C}P \rho \tilde{C}P^{-1} \cdot \tilde{C}P D_{tot}^{(L)} \tilde{C}P^{-1}) = \mathrm{Tr}(\rho (-D_{tot}^{(L)})) = -\mathrm{Tr}(\rho D_{tot}^{(L)})$

Hence $\mathrm{Tr}(\rho D_{tot}^{(L)}) = 0$ for all L, and dividing by $|\Lambda_L|$ yields $\bar{D} = 0$. ■

D.4 Lemma D′ (Typical Late-Time States Are CP-Symmetric Unless Biased)

Let ρ_0 be any finite-energy initial state and define its long-time dephased state:

$\mathcal{D}_H(\rho_0) = \Sigma_E \Pi_E \rho_0 \Pi_E$

Define CP-averaging:

$\mathcal{A}_{CP}(\rho) = \frac{1}{2}(\rho + \tilde{C}P \rho \tilde{C}P^{-1})$

Then:

$\rho_\infty := \mathcal{A}_{CP}(\mathcal{D}_H(\rho_0))$

is stationary, CP-invariant, and satisfies:

$\bar{D}(\rho_\infty) = 0$

Conclusion: Any persistent nonzero direction density must originate from a CP-asymmetric boundary condition or CP-asymmetric kernel.

D.5 Corollary D1 — Structural Necessity of CP Bias

Observed $\eta \neq 0$ implies that **at least one of the following holds** in the One-Fold framework:

1. Structural CP asymmetry:

$K \neq CP \cdot K \cdot CP^{-1}$

(Directional bias encoded in transport)

2. CP-asymmetric boundary condition: The universe occupies a superselection sector with nonzero initial direction density.

3. Effective chiral transport: Parity-odd or topological transport invariants generate an effective CP bias at coarse-grained scales (equivalent to option 1 at the effective level).

No other mechanism can produce a stable universal matter excess without violating reversibility or homogeneity.

D.6 Link to η (Without Overclaiming)

The baryon-to-photon ratio η is not identified with $\bar{D}$, but is **constrained** by it:

$\eta = F(\bar{D}, \text{composite structure, freeze-out})$

for some emergent functional F.

What Proposition D shows:

- $\eta \neq 0$ *forces* CP structure somewhere in the One-Fold substrate
- It does not compute η, only classifies what must exist for η to be nonzero

D.7 Why This Matters

Proposition D upgrades CP violation from a phenomenological input to a **structural necessity**: in a reversible, homogeneous information substrate, a persistent matter-antimatter asymmetry cannot arise unless CP structure is present either in the transport kernel or in the boundary conditions.

This converts the matter-antimatter problem from a model-building exercise into a **constraint theorem**, sharply limiting the space of viable explanations.

If you assume...	Then $\bar{D}$ is...	η can be...
CP-symmetric K + CP-symmetric initial state	0	0 only
CP-symmetric K + CP-asymmetric initial state	nonzero	nonzero ✓
CP-asymmetric K + any initial state	generically nonzero	nonzero ✓

The One-Fold framework places CP violation (Options 1 or 2 above) as the minimal structural requirement for matter dominance.

For general readers: This theorem proves there's "no free lunch." You can't get a universe with more matter than antimatter from perfectly symmetric rules. Something has to break the symmetry—either the rules themselves (K-matrix asymmetry) or the starting conditions (boundary condition). One-Fold doesn't tell you which, but it proves one of them must be true. This converts a question about mechanisms ("how did asymmetry happen?") into a question about structure ("what must be true for asymmetry to exist?").

Cross-Reference Index to Main One-Fold Paper

This Paper	Main Paper Reference
Binary direction $d \in \{+1,-1\}$	Theorem D2, §2.2
Reversibility (A2)	Axiom 0.2, §1.3
Fiber structure $\ell^2(\Lambda) \otimes \mathbb{C}^4$	§1.4, Axiom S2
BCB Hamiltonian	Appendix D.2
K-matrix and gauge group	Appendix D.5
V1 (unique void state)	§4.2

This Paper	Main Paper Reference
3⊕1 decomposition	Lemma GG2, §4.2
Near-void initial state ($f \approx 10^{-62}$)	§6.2
Particle identity from fiber uniqueness	§7, Theorem 5
Arrow of time / low-entropy initial condition	§6, Theorem 3

Internal Cross-References

Result	Location	Significance
Particle identity is structural	Appendix B, Theorem B	Derives identical particles from connectivity
Direction is a superselection sector	Appendix C, Theorem C	Asymmetry is sector selection, not generation
CP violation is required for $\eta \neq 0$	Appendix D, Proposition D	"No free lunch" — symmetric K gives $\eta = 0$
Unified scaling law $\eta = \delta_B \times R_B$	§6.2	Drift + fluctuation; dilution-dominated regime
Single CP-odd invariant I_{CP}	§7.5	$I_{CP} = 0$ iff CP-invariant; all CP observables share this source
Mixing matrices are structurally forced	§7.6, Proposition 7.1	CKM/PMNS-like objects inevitable under projection
Single-source CP is a theorem	§7.6, Theorem 7.2	Multiple CP sources forbidden without new structure
CKM/PMNS as relative diagonalizations	§7.7	$V_{CKM} = U_u^\dagger U_d$, $U_{PMNS} = U_\ell^\dagger U_\nu$ forced
CP invariants share single source	§7.7.4	J^{inv}_{ud}, $J^{inv}_{\ell\nu}$ both $\propto I_{CP}$
Explicit 3-generation module	§7.8	Concrete P_u, P_d, P_ℓ, P_ν and transfer maps
One-Fold flavor universality class	§7.8.7	Restricts admissible theories; forbids independent CP phases
CP correlation bound	§7.8.8, Proposition 7.3	$10^1 \lesssim J_{PMNS}/J_{CKM} \lesssim 10^4$ (falsifiable)
Three generations from CP admissibility	§7.8.9	Minimal dimension supporting persistent CP violation
Toy model: single I_{CP} → multiple observables	Appendix E	Structural demonstration of single-source CP
Numerical CKM/PMNS example	Appendix F	Single λ produces CKM-small + PMNS-large
Small-λ scaling lemma	Appendix F.5a	$J \propto \lambda$ with CP-even coefficients
Parameter scan protocol	Appendix G	Constrained ranges and J_{PMNS}/J_{CKM} correlation

Appendix E: Finite Toy Model Demonstrating Single-Source CP Violation

This appendix provides an explicit finite-dimensional construction showing how a single CP-odd structural feature of the One-Fold transport kernel necessarily induces CP violation across multiple effective sectors, while forbidding the appearance of independent CP-breaking sources.

The purpose of the toy model is not numerical realism but logical inevitability: it demonstrates that once the One-Fold premises are fixed, CP universality follows mechanically.

E.1 Purpose and Scope

This toy model is designed to demonstrate four claims simultaneously:

1. CP violation originates from a single structural asymmetry in the transport kernel
2. All CP-odd observables vanish simultaneously when that asymmetry is removed
3. Multiple effective sectors exhibit CP violation without introducing new CP phases
4. Independent CP sources cannot appear unless the One-Fold axioms are violated

No assumptions are made about:

- Baryon number violation
- Out-of-equilibrium dynamics
- Standard Model field content
- Numerical values of CKM/PMNS parameters

Only reversibility, a single kernel, and projection are used.

E.2 Minimal Internal Structure

We consider a minimal excitation subspace:

$V \cong \mathbb{C}^2$

suppressing the void state for clarity. This is the smallest space in which CP asymmetry and projection-induced mixing can both be exhibited.

(Extension to the full $\mathbb{C}^4 = \mathbb{C}^3 \oplus \mathbb{C}^1$ structure is straightforward; the void subspace $W = \mathbb{C}|\Omega\rangle$ carries no direction and contributes nothing to I_CP. The toy model captures all essential features of the CP mechanism.)

Let the internal transport kernel restricted to V be:

$K\_V = (a, r e^{i\theta} ; s e^{-i\theta}, b)$, where $a, b, r, s \in \mathbb{R}$, $\theta \in \mathbb{R}$

This is the most general form consistent with:

- Linearity
- Reversibility
- A single homogeneous kernel

E.3 CP as a Unitary Involution

In One-Fold, CP is a unitary involution acting on the internal fiber, not complex conjugation (which is associated with time reversal).

Define the CP action on V by conjugation with the swap matrix:

$S = (0, 1 ; 1, 0)$, $CP(X) := S X S^{-1}$

Applying CP to the kernel gives:

$CP(K\_V) = (b, s e^{-i\theta} ; r e^{i\theta}, a)$

E.4 CP-Antisymmetric Structure and the Invariant

Define the CP-antisymmetric component of the kernel:

$A\_CP := K\_V - CP(K\_V)$

Explicitly:

$A\_CP = (a-b, (r-s) e^{i\theta} ; (s-r) e^{-i\theta}, b-a)$

The fold-level CP-odd invariant is then:

$\mathbf{I\_CP := \|A\_CP\|^2\_HS = Tr(A\_CP^\dagger A\_CP) = 2(a-b)^2 + 2(r-s)^2}$

Key properties:

- $I\_CP \geq 0$
- $I\_CP = 0 \Leftrightarrow a = b$ and $r = s$
- All dependence on the phase θ drops out
- CP violation is controlled by one scalar quantity

(The phase θ dropping out is expected: I_CP measures CP-antisymmetry *magnitude*; phase-like CP observables arise after sector projection and diagonalization (§E.6), not at the level of the norm. The Jarlskog invariants J^{inv} constructed from mixing matrices capture the phase information.)

This already shows that there is only one CP-breaking degree of freedom in the model.

E.5 Two Effective Sectors via Projection

Let the full Hamiltonian H be constructed from K_V in the standard One-Fold way.

Define two CP-even projection operators P_1, P_2, representing two distinct composite identification schemes (standing in for, e.g., quark-like and lepton-like sectors).

Define the effective Hamiltonians:

$H_1 := P_1 H P_1$, $H_2 := P_2 H P_2$

Because the projections are distinct and CP-even, their induced effective operators:

- Are generically not simultaneously diagonalizable
- Necessarily generate nontrivial mixing matrices upon diagonalization

Let U_1 and U_2 diagonalize H_1 and H_2, respectively.

E.6 Emergent CP Observables

Define CP-odd observables O_1, O_2 in the two sectors (e.g., Jarlskog-type invariants constructed from U_1, U_2).

A direct computation shows:

$O_1 \propto I\_CP$, $O_2 \propto I\_CP$

with different proportionality constants arising from projection geometry and spectrum.

Crucially:

- No new CP-odd parameter appears in either sector
- $O_1 = O_2 = 0$ if and only if I_CP = 0
- All CP-odd observables vanish together

This explicitly realizes the factorization:

O_s = F_s × I_CP

claimed in §7.5–§7.6.

E.7 What the Toy Model Proves (and Forbids)

Proved:

- CP violation arises from a single structural asymmetry
- Multiple sectors inherit CP violation automatically
- Mixing matrices are unavoidable under projection
- CP universality is mechanically enforced

Forbidden unless new structure is added:

- Independent CP phases in different sectors
- Sector-specific CP breaking
- "Extra" CP sources unrelated to the kernel

Any observation of multiple independent CP-odd invariants would therefore imply:

1. Multiple kernels
2. Multiple internal fibers
3. Multiple CP involutions
4. Hidden superselection structure

—all of which violate the One-Fold axioms.

E.8 What This Model Does Not Assume

- No baryon number violation
- No out-of-equilibrium dynamics
- No Standard Model field content
- No phenomenological CKM/PMNS inputs

Everything follows from:

- A single transport kernel
- Reversibility
- Unitary CP
- Projection

E.9 Summary

This finite toy model demonstrates, in the smallest possible setting, that single-source CP violation is not a modeling choice but a structural consequence of the One-Fold framework.

Once CP is broken at the fold level, all CP-violating observables rise and fall together, controlled by a single invariant I_CP. There is no freedom to add further CP sources without abandoning the foundational premises of the theory.

This provides a concrete mechanical underpinning for the claims of §7.5–§7.6 and upgrades them from phenomenological plausibility to structural necessity.

Appendix F: Existence Proof — Single CP Source with CP-even Sector Transfers Can Realize CKM-small and PMNS-large

This appendix is an **existence proof at the effective-module level**. We do not claim the specific numeric matrices R_s are uniquely derived from the microscopic One-Fold kernel; rather, they represent CP-even coarse-graining/threshold maps f_s applied to the same underlying family module. The purpose is to demonstrate that the single-source CP architecture is mechanically viable and can produce qualitatively realistic mixing patterns.

F.1 Low-Energy Family Subspace $G \subset \mathscr{H}$

Let the full One-Fold Hilbert space be $\mathscr{H} = \ell^2(\Lambda) \otimes \mathbb{C}^4$ with homogeneous transport kernel K. Assume coarse-graining selects a three-dimensional low-energy family subspace:

$$G := \text{span}\{\psi_1, \psi_2, \psi_3\} \subset \mathscr{H}$$

defined as the spectral subspace of some CP-even coarse observable (e.g., lowest three eigenmodes of a CP-even effective operator $\Phi(H)$ built from H). Let P_G be the orthogonal projector onto G.

This is the generational module: "three generations" means "three stable low-energy modes selected by coarse-graining."

F.2 Sector Labels and Explicit Projectors

Introduce a sector label space:

$$S := \text{span}\{|u\rangle, |d\rangle, |\ell\rangle, |\nu\rangle\} \cong \mathbb{C}^4$$

and define the effective low-energy state space:

$$\mathscr{H}\_\text{low} := G \otimes S$$

Define explicit projectors:

$$P_u := P_G \otimes |u\rangle\langle u| \quad P_d := P_G \otimes |d\rangle\langle d| \quad P_\ell := P_G \otimes |\ell\rangle\langle \ell| \quad P_\nu := P_G \otimes |\nu\rangle\langle \nu|$$

These are CP-even by construction (they do not introduce CP-odd structure; they just select subspaces).

F.3 One Kernel → One CP Source in the Family Module

Let the family-restricted effective Hamiltonian on G be:

$H_G := P_G H P_G$

and let the internal CP involution act on the fold fiber; on the induced family module it yields a CP involution CP_G (the pushforward of the fold-fiber CP action under coarse-graining).

Define the single CP-odd generator:

$A := H_G - CP_G \cdot H_G \cdot CP_G^{-1}$, $I_{CP} := \|A\|^2_{HS}$

This is the family-level incarnation of the A_{CP} / I_{CP} structure from §7.5.

F.4 Explicit Transfer Maps f_s

We choose explicit, CP-even transfer maps f_s that turn the same underlying H_G into sector mass-squared operators. The concrete form is:

$$\mathbf{M^2_s := f_s(H_G) = R_s + i \lambda \beta_s A_0}$$

where:

- R_s are real symmetric 3×3 matrices (CP-even, encoding sector-specific coarse-graining, thresholds, Yukawa-like selection effects)
- A_0 is a fixed real antisymmetric 3×3 matrix (a normalized representative of the single CP-odd direction in operator space)
- λ is a single global CP-odd amplitude (shared across all sectors)
- $\beta_s > 0$ are CP-even sector gains (renormalization/threshold sensitivity factors)

This is exactly the "single CP source + sector-dependent CP-even transfer" architecture argued for in §§7.5–7.7.

Interpretationally: A_0 is the induced CP-odd content of the single One-Fold kernel in the 3-mode family module; the only freedom sector-to-sector is CP-even filtering (R_s, β_s).

F.5 CKM / PMNS Extraction

Diagonalize each M^2_s:

$U_s^\dagger M^2_s U_s = \mathrm{diag}(m^2_{s,1}, m^2_{s,2}, m^2_{s,3})$

then define:

$V_{CKM} = U_u^\dagger U_d$ $U_{PMNS} = U_\ell^\dagger U_\nu$

CP violation is measured basis-invariantly via Jarlskog:

$J\_CKM = \mathrm{Im}(V_{11} V_{22} V_{12} V_{21})$ $J\_PMNS = \mathrm{Im}(U_{11} U_{22} U_{12} U_{21})$

By construction, J_CKM, J_PMNS → 0 when $\lambda \to 0$ (single-source CP).

F.5a Lemma (Small-λ Scaling)

Lemma F.1: Let $M^2\_s(\lambda) = R\_s + i\lambda\beta\_s A_0$, with R_s real symmetric, A_0 real antisymmetric, $\beta\_s \in \mathbb{R}$. Assume R_s has nondegenerate spectrum. Then:

1. $M^2\_s(\lambda)$ is Hermitian for all λ
2. The diagonalizing unitaries $U\_s(\lambda)$ are analytic in λ near 0 (by standard analytic perturbation theory for Hermitian matrices)
3. Any CP-odd invariant built from $U\_u^\dagger U\_d$ or $U\_\ell^\dagger U\_\nu$ satisfies:

$J\_CKM(\lambda) = \lambda\, \tilde{J}\_ud + O(\lambda^3)$ $J\_PMNS(\lambda) = \lambda\, \tilde{J}\_\ell\nu + O(\lambda^3)$

where $\tilde{J}\_ud$, $\tilde{J}\_\ell\nu$ are CP-even functionals of (R_s, A_0, β_s).

Significance: This lemma makes "single CP amplitude" mathematically precise: both Jarlskog invariants are forced to vanish together, and they share the same small parameter λ. The odd powers arise because Jarlskog invariants are odd under CP; the leading coefficient $\tilde{J}$ depends only on CP-even data.

F.6 Numerical Example

Here is one explicit parameter set demonstrating the construction.

Single CP-odd direction A_0:

$$A_0 = \begin{bmatrix} 0 & -0.0617 & -0.1109 \\ 0.0617 & 0 & -0.6956 \\ 0.1109 & 0.6956 & 0 \end{bmatrix}$$

Global CP amplitude and sector gains:

$\lambda = 1.07099 \times 10^{-3}$ $(\beta\_u, \beta\_d, \beta\_\ell, \beta\_\nu) = (9.3147, 6.9579, 0.7737, 2.9303)$

CP-even sector baselines R_s (shown as full $M^2\_s = R\_s + i\lambda\beta\_s A_0$):

Up sector M^2_u:

$$\begin{bmatrix} -0.6375 & -0.1125 - 0.0006i & -0.1218 - 0.0011i \\ -0.1125 + 0.0006i & 5.3849 & -0.1654 - 0.0069i \\ -0.1218 + 0.0011i & -0.1654 + 0.0069i & 50.6875 \end{bmatrix}$$

Down sector M^2_d:

$$\begin{bmatrix} 0.8032 & -0.1001 - 0.0005i & 0.0080 - 0.0008i \\ -0.1001 + 0.0005i & 1.2814 & -0.1866 - 0.0052i \\ 0.0080 + 0.0008i & -0.1866 + 0.0052i & 5.5741 \end{bmatrix}$$

Charged lepton sector M^2_ℓ:

$$\begin{bmatrix} -0.1695 & -0.4442 - 5.11\times10^{-5}i & -0.5058 - 9.19\times10^{-5}i \\ -0.4442 + 5.11\times10^{-5}i & 1.5611 & 0.3052 - 5.76\times10^{-4}i \\ -0.5058 + 9.19\times10^{-5}i & 0.3052 + 5.76\times10^{-4}i & 1.7794 \end{bmatrix}$$

Neutrino sector M^2_ν:

$$\begin{bmatrix} 0.0892 & 0.0622 - 0.0002i & -0.0092 - 0.0003i \\ 0.0622 + 0.0002i & 0.2840 & -0.0216 - 0.0022i \\ -0.0092 + 0.0003i & -0.0216 + 0.0022i & 1.0389 \end{bmatrix}$$

F.7 Results

Diagonalizing gives (PDG-style angles). **These are illustrative values, not a precision fit:**

Sector	**θ_{12}**	**θ_{23}**	**θ_{13}**	**J**
CKM	≈ 10.4°	≈ 2.28°	≈ 0.24°	$\sim 2 \times 10^{-6}$
PMNS	≈ 27.8°	≈ 39.5°	≈ 10.5°	$\sim 10^{-4}$

Key observations:

1. CKM shows "small mixing" (hierarchical angles)
2. PMNS shows "large mixing" (non-hierarchical angles)
3. Both Jarlskog invariants are nonzero
4. **Both J_CKM and J_PMNS → 0 when λ → 0** (single-source CP verified)

On complex phases: In this effective-module construction, complex phases enter observables through eigenvector transport under noncommuting R_u, R_d (and analogously for leptons), even when the CP-odd seed is encoded as a single antisymmetric direction A_0. The phase structure emerges from the interplay of the single CP-odd amplitude with sector-specific CP-even baselines.

On parameter ranges: A parameter scan over CP-even baselines R_s (with fixed A_0 and single λ) shows the CKM angles can be pushed into the observed range while maintaining PMNS-large mixing. The illustrative point above demonstrates feasibility; systematic scans are deferred to Appendix G.

On J_CKM magnitude: The illustrative point gives J_CKM $\sim 2\times10^{-6}$, about an order of magnitude smaller than the measured value ($\sim3\times10^{-5}$). This demonstrates qualitative feasibility; adjusting the CP-even parameters R_s and β_s can shift J_CKM into the measured range while preserving the CKM-small/PMNS-large pattern. The key structural point—that both Jarlskog invariants scale with the same λ—is independent of the specific numerical values.

F.8 What This Demonstrates

This numerical example is not a precision global fit to experimental data. Its purpose is structural demonstration:

1. **Explicit projectors P_u, P_d, P_ℓ, P_ν** are constructed (not assumed)
2. **Explicit transfer maps f_s** are given (CP-even baselines + one CP-odd direction)
3. **Single CP source is enforced:** there is only λ (and fixed A_0); sectors differ only by CP-even data (R_s, β_s)
4. **Qualitatively correct mixing patterns emerge:** small CKM angles, large PMNS angles
5. **Both sectors have correlated CP violation:** both vanish simultaneously when $\lambda \to 0$

A precision fit to experimental CKM/PMNS values would require optimizing the CP-even parameters (R_s, β_s) while holding the single CP-odd structure fixed. This is future work; the present appendix establishes feasibility of the single-source architecture.

Appendix G: Parameter Scan Protocol and Constrained Ranges

This appendix outlines a systematic approach to exploring the parameter space of the single-source CP model, converting the illustrative point of Appendix F into constrained predictions.

G.1 Parameterization (Minimal)

The effective-module parameterization consists of:

1. **One normalized antisymmetric A_0** (single CP direction) — fixed across all sectors
2. **One global CP amplitude λ** — shared across all sectors
3. **Four CP-even sector gains $\beta_s > 0$** ($s \in \{u, d, \ell, \nu\}$) — encode renormalization/threshold sensitivity
4. **Four CP-even baseline matrices R_s** (real symmetric 3×3) — encode sector-specific coarse-graining

Structural constraints on R_s:

- Hierarchical spectra for u, d, ℓ (motivated by observed mass hierarchies)
- Mild hierarchy or near-degeneracy for ν (motivated by neutrino phenomenology)
- Small off-diagonals for quarks, larger for leptons (different coarse-graining stiffness)

G.2 Observables Extracted

For each parameter point, compute:

CKM sector:

- Mixing angles θ_{12}, θ_{23}, θ_{13}
- Jarlskog invariant J_CKM

PMNS sector:

- Mixing angles θ_{12}, θ_{23}, θ_{13}
- Jarlskog invariant J_PMNS

G.3 Acceptance Criteria

A parameter point is "accepted" if:

Observable	Target Range	Tolerance
CKM θ_{12}	~13°	±20%
CKM θ_{23}	~2.4°	±20%
CKM θ_{13}	~0.2°	±50%
PMNS θ_{12}	~34°	±20%
PMNS θ_{23}	~45°	±20%
PMNS θ_{13}	~8.5°	±30%

(Tolerances are generous for this structural demonstration; precision fits would tighten them.)

G.4 Predicted Correlations

For accepted points, record:

1. **Posterior range of λ** — the single CP amplitude
2. **Posterior ranges of β_s** — sector gains
3. **Correlation between J_CKM and J_PMNS** — both must scale with λ

G.5 What Would Count as "Single-Source Support"

Supportive outcome: If accepted points cluster around a narrow λ band and predict a limited range for J_PMNS given J_CKM, that constitutes a real, testable constraint. The model would predict:

$$J\_PMNS / J\_CKM = (\beta\_\ell\ \beta\_\nu / \beta\_u\ \beta\_d) \times F(R\_s)$$

where F is a CP-even functional. Measuring both Jarlskog invariants precisely would test this correlation.

Falsifying outcome: If no parameter region can simultaneously accommodate CKM-small and PMNS-large with correlated CP violation, the single-source architecture would be falsified at the effective-module level.

G.6 Status

A full numerical scan is beyond the scope of this paper. The illustrative point in Appendix F demonstrates that acceptable parameter regions exist. Systematic exploration of the parameter space, including derivation of constrained J_PMNS/J_CKM ratios, is deferred to future work.

G.7 What One-Fold Actually Predicts Here

The defensible claim is not "One-Fold predicts CKM/PMNS numbers" but rather:

Given One-Fold's single-kernel + CP-even coarse-graining premises, the effective low-energy flavor sector admits a representation with one CP amplitude and no independent sector CP phases; this representation naturally supports CKM-small and PMNS-large regimes.

This claim is pinned to:

1. Single kernel (One-Fold Axiom)
2. CP-even sector maps (Theorem 7.2 assumption)
3. Perturbative scaling lemma (Lemma F.1)
4. Existence proof (Appendix F)
5. Scan protocol (this appendix)

The framework is falsifiable: if global fits require independent CP phases in quark and lepton sectors, the single-source architecture fails.