The Recognition Instrument for Abiogenesis:
Duplex Geometry, φ–Timed Coherence, and Templated Replication with Falsifiers

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Design note: This manuscript presents a standards-ready, audit-first blueprint for abiogenesis grounded in Recognition Science (RS). It emphasizes falsifiable predictions, portable instrumentation, and safety-by-design.

Origin of Life under Recognition Science (RS): A New, Detailed Outline

Working Title

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One–paragraph Thesis

Life's core loop—replication with heritable variation—emerges when matter is driven by a universal *recognition instrument*: a convex, dimensionless ledger J, an eight–beat φ–timed schedule, and a mid–IR coherence quantum ($\sim 724\ \mathrm{cm}^{-1}$). Under minimal polymer constraints, this instrument makes a counter–wound duplex the unique low–overhead geometry, forces templated copying as a fixed point of the gate, and yields a bounded evolvability window from timing jitter. The blueprint is chemistry–agnostic, specified by audit surfaces and falsifiers, and engineered for reproducibility and safety.

1 Introduction

1.1 Problem statement

Recipe–centric origin–of–life narratives lack a unifying, quantitative *instrument*. Reproducibility is low; falsifiers are vague; and "success" often rests on post hoc criteria rather than preregistered audits. The field needs a portable, parameter–free framework that predicts what *must* happen and specifies how to test it.

1.2 Claim (instrument–first)

Given the Recognition Science (RS) ledger $J(x) = \frac{1}{2}(x + 1/x) - 1$, an eight–beat φ–timed schedule, and a mid–IR coherence band (near 724 cm^{-1}), a counter–wound duplex geometry and templated replication are *forced* in three dimensions under locality and complementarity constraints. Evolvability then follows from controlled timing jitter under the same instrument.

1.3 Contributions

(i) Variational derivation of duplex geometry with φ ratio constraints (pitch and groove bands).

(ii) Phase–resolved energetics and the LISTEN/LOCK/BALANCE gate tied to the coherence band.

(iii) A fixed–point theorem for templating (complement copying as the unique gate fixed point).

(iv) An evolvability window derived from timing noise (jitter–induced, bounded mutation spectrum).

(v) Quantitative falsifiers and audit surfaces (predeclared pass/fail thresholds).

(vi) A cross–chemistry universality protocol (same instrument, no per–sequence dials).

(vii) Safety and standards: open conformance tests, signed logs, and containment.

1.4 Scope & non–claims

We prove a *necessary and sufficient* instrument blueprint for replication with heritable variation. We do *not* claim specific geochemical recipes, planetary histories, or organismal complexity. The focus is the recognition instrument itself—its geometry, timing, energetics, and auditable consequences.

2 RS Primer (minimal tools)

2.1 Ledger J and recognition ratios

We use the convex, symmetric *ledger* cost

$$J(x) \;=\; \tfrac{1}{2}\left(x + \frac{1}{x}\right) - 1, \qquad x > 0,$$

with $J(1) = 0$, $J'(1) = 0$, and $J''(x) = x^{-3} > 0$ (strict convexity). Symmetry $J(x) = J(1/x)$ treats overshoot and undershoot equally, so J measures *distance from target* without bias. Diagnostics y_i are normalized by *declared* targets $y_i^\star > 0$ to form dimensionless *recognition ratios*

$$r_i \;:=\; \frac{y_i}{y_i^\star} \in \mathbb{R}_{>0}.$$

Because r_i is invariant under any common rescaling $y_i \mapsto \alpha y_i$, $y_i^\star \mapsto \alpha y_i^\star$, it *outlaws unit games*: the controller and audits depend only on physics, not on instrument units. The aggregate objective is

$$\mathcal{L}(r) \;=\; \sum_i w_i\, J(r_i), \qquad w_i > 0,$$

with weights set by transport sensitivity (declared in calibration).

2.2 Eight–beat φ–timed schedule

In $D{=}3$, we partition a control period T into eight windows

$$0 = t_0 < t_1 < \cdots < t_8 = T, \qquad W_\ell = [t_\ell, t_{\ell+1}), \quad \Delta t_\ell := t_{\ell+1} - t_\ell,$$

with

$$\sum_{\ell=0}^{7} \Delta t_\ell = T, \qquad \frac{\Delta t_{\ell+1}}{\Delta t_\ell} \in \{\varphi,\ \varphi^{-1}\} \quad \text{(indices mod 8)},$$

where $\varphi = (1+\sqrt{5})/2$. The golden ratio's *badly approximable* property (Diophantine separation) suppresses low–order resonances between actuator updates and modal responses, reducing *modal collisions* and cross–interference relative to co–phased or equal–spaced timing. Actuators are assigned phase sets $\Pi(a) \subset \{0, \ldots, 7\}$ and may change setpoints only when the active window $\ell \in \Pi(a)$; dwell and slew constraints are enforced inside windows.

2.3 Coherence quantum

There is a single coherence budget for recognition at hydrogen–bond scale,

$$E_{\text{coh}} \ \approx\ 0.09 \text{ eV} \quad \Longleftrightarrow \quad \tilde{\nu}_{\text{coh}} \ \approx\ 724 \text{ cm}^{-1},$$

(using $E = hc\,\tilde{\nu}$). The gate operates as a three–phase cycle:

LISTEN — low drive; align and sample partners near the band without forcing binding.
LOCK — brief, φ–scheduled energy delivery at $\tilde{\nu}_{\text{coh}}$ to stabilize correct contacts; ledger drops.
BALANCE — release excess; incorrect contacts fall away; transport resumes.

Phase timing is fixed a priori (eight–beat schedule). *Energy audits* declare Pass/Fail by thresholds on (i) lock–band occupancy and (ii) ledger change, e.g.

$$\mathsf{Pass} \iff \underbrace{\mathrm{Occ}_{724}}_{\text{spectral proxy}} \geq \Theta_{\text{spec}} \quad \wedge \quad \underbrace{\Delta\mathcal{L}}_{\text{ledger drop}} \geq \Lambda,$$

optionally with safety metrics (temperature, photodose) bounded. Only Pass cycles are admitted; otherwise actions are modified or rejected, and the schedule advances without actuation.

3 Formal Setup (state, constraints, audits)

3.1 State and configuration space

We model two polymer backbones with complementary faces in a local solvent. Each backbone is a C^2 space curve with Frenet–Serret frame:

$$\gamma_k : [0, L_k] \to \mathbb{R}^3, \qquad (\mathbf{t}_k, \mathbf{n}_k, \mathbf{b}_k)(s) = \text{frame of } \gamma_k, \qquad k \in \{1, 2\}.$$

Complementary *faces* are unit vectors rigidly attached to monomer sites:

$$\mathbf{f}_k(s) \in \mathbb{S}^2, \qquad \mathbf{f}_k \perp \mathbf{t}_k, \quad k \in \{1, 2\},$$

encoding docking orientation (H–bond alignment, π–stacking alignment). The solvent state collects intensive fields (treated as exogenous within one control period):

$$\vartheta = (T,\ I,\ pH,\ \eta,\ \ldots),$$

for temperature, ionic strength, acidity, viscosity, etc.

System state. The instantaneous state is

$$x = (\gamma_1, \gamma_2,\ \mathbf{f}_1, \mathbf{f}_2,\ \sigma,\ \vartheta),$$

where σ is a discrete *contact register* on aligned site pairs (s_1, s_2) taking values in

$$\sigma(s_1, s_2) \in \{\textsf{free},\ \textsf{bind-ready},\ \textsf{locked}\}.$$

Admissible moves (per gate). On each φ–timed window W_ℓ the following local moves may occur (subject to constraints below):

- *bind*: bind-ready $\to$ locked at a site pair within the H–bond window;
- *unbind*: locked $\to$ free outside the stability band;
- *slide*: relative tangential translation $(s_1, s_2) \mapsto (s_1 + \delta, s_2 - \delta)$;
- *rotate*: local helical twist about $\mathbf{t}_k$ within torsion bounds.

Transport (Brownian drift of γ_k and rotation of $\mathbf{f}_k$) proceeds continuously but is *gated* by the schedule.

3.2 Constraints

All moves obey hard physical constraints:

- **Locality.** Interactions are local with cutoff $d_{\max}$: only pairs with $\|\gamma_1(s_1) - \gamma_2(s_2)\| \le d_{\max}$ may transition to bind-ready.
- **Sterics.** Minimum separation between non-complement sites and self–avoidance of each backbone; excluded–volume radius $r_{\min}$.

  $$\|\gamma_k(s) - \gamma_k(s')\| \ge 2r_{\min} \quad (|s - s'| > \delta s_{\min}).$$

- **Torsion/curvature limits.** With curvature κ_k and torsion τ_k,

  $$0 \le \kappa_k(s) \le \kappa_{\max}, \qquad |\tau_k(s)| \le \tau_{\max}.$$

- **H–bond window.** A docked pair must satisfy distance/angle tolerances

  $$d_{\mathrm{H}} \in [d_{\min}, d_{\max}], \qquad \angle(\mathbf{f}_1, -\mathbf{f}_2) \le \alpha_{\max}, \qquad \angle(\mathbf{t}_1, \mathbf{t}_2) \le \beta_{\max}.$$

- **No per–sequence knobs.** Energetics and timing are sequence–indifferent at the gate: the drive, thresholds, and acceptance tests are fixed a priori and do not vary by monomer identity.

3.3 Action functional

The instrument drives the system with φ–timed envelopes $a_\ell(t)$ on windows W_ℓ, centered near the coherence band. The *total action* over one period $[0, T]$ is the time integral of a recognition ledger plus a transport ledger:

$$\mathcal{S}[x, \{a_\ell\}] = \underbrace{\sum_{\ell=0}^{7} \int_{W_\ell} \sum_i w_i\, J(r_i(x(t)))\, dt}_{\text{recognition}} \;+\; \underbrace{\int_0^T \Big(\lambda_{\text{slide}} \sum_k \|\dot{\gamma}_k^{\parallel}\|^2 + \lambda_{\text{twist}} \sum_k \dot{\theta}_k^2\Big)\, dt}_{\text{transport}},$$

where $r_i = y_i / y_i^\star$ are dimensionless proxies (e.g., lock–band occupancy, geometric residuals), $\dot{\gamma}_k^{\parallel}$ is tangential sliding speed, and $\dot{\theta}_k$ is local twist rate. Control enters via

$$y_{\text{spec}}(t) = \mathsf{Spec}(x(t)) \cdot a_{\ell(t)}(t),$$

modulating the spectral channel near 724 cm^{-1}. The induced dynamics are constrained by the schedule: setpoint changes (e.g., illumination intensity, temperature micro–pulses) are admissible only at the beginning of each window, and their envelopes are fixed up to declared amplitudes.

3.4 Audit surfaces

We declare *pre–registered* pass/fail surfaces with fixed thresholds:

Geometry band. From fitted duplex geometry $\mathcal{G} = (P, G_{\min}, G, \rho_{/\min})$ (pitch, minor/major grooves, ratio), require

$$P \in [P_-, P_+], \quad G_{\min} \in [G_{\min,-}, G_{\min,+}], \quad G \in [G_{,-}, G_{,+}], \quad \rho_{/\min} \in [\rho_-, \rho_+],$$

with bands centered on the φ predictions (e.g., $\rho_{/\min} \approx \varphi$).

Lock–band occupancy. Phase–resolved spectral occupancy near 724 cm^{-1} must exceed a threshold during LOCK:

$$\mathrm{Occ}_{724} = \frac{1}{|W_{\text{LOCK}}|} \int_{W_{\text{LOCK}}} y_{\text{spec}}(t)\, dt \;\geq\; \Theta_{\text{spec}}.$$

Ledger margin. The recognition ledger must drop by at least Λ during LOCK:

$$\Delta\mathcal{L} = \mathcal{L}_{\text{pre}} - \mathcal{L}_{\text{post}} \;\geq\; \Lambda.$$

Safety metrics. Cumulative photodose, peak temperature, and local heating rates bounded:

$$\text{Dose} \leq D_{\max}, \qquad T \leq T_{\max}, \qquad \dot{T} \leq R_{\max}.$$

Certificate (per cycle). With M–window aggregation as in Sec. **??** (fusion paper analogue), declare

$$\mathsf{Pass} \iff \Big(\mathcal{G} \in \text{bands}\Big) \;\wedge\; \Big(\mathrm{Occ}_{724} \geq \Theta_{\text{spec}}\Big) \;\wedge\; \Big(\Delta\mathcal{L} \geq \Lambda\Big) \;\wedge\; \Big(\text{Safety} \leq \text{bounds}\Big),$$

otherwise $\mathsf{Modify/Reject}$. All decisions, timing, and proxies are logged and signed; thresholds are versioned and hash–committed before experiments.

4 Geometry of the Minimal Duplex

4.1 Variational problem

We seek the stationary geometry that minimizes cumulative ledger cost over binding, unbinding, and smooth strand transport, under the hard constraints of Sec. 3. Let each backbone be a C^2 space curve $\gamma_k : [0, L] \to \mathbb{R}^3$ with curvature κ_k and torsion τ_k, and let $\mathbf{f}_k$ denote the complementary face vectors rigidly attached to the monomers (orthogonal to $\mathbf{t}_k$). Over one spatial period Λ (one helical turn), the *geometric* action is

$$\mathcal{A}[\gamma_1, \gamma_2, \mathbf{f}_1, \mathbf{f}_2] \;=\; \int_0^{\Lambda} \Big[\underbrace{w_{\text{dock}}\, J(r_{\text{dock}}(\delta, \alpha, \beta))}_{\text{binding/alignment}} \;+\; \underbrace{A\sum_{k=1}^{2} \kappa_k^2 \;+\; C\sum_{k=1}^{2} \tau_k^2}_{\text{transport smoothness}} \;+\; \underbrace{w_{\text{face}}\, J(r_{\text{face}}(\mathbf{f}_1, \mathbf{f}_2))}_{\text{face alignment}} \Big]\, ds, \tag{1}$$

subject to the constraints: (i) locality and sterics (self-avoidance; excluded radius); (ii) H–bond window $d_{\min} \le \delta \le d_{\max}$ and angular tolerances $\alpha \le \alpha_{\max}$, $\beta \le \beta_{\max}$; (iii) no per–sequence knobs (the integrand is sequence–indifferent at the gate). Here δ is inter–strand separation, and (α, β) capture face–to–face and tangent–to–tangent misalignments. Control enters only through the *timing* of gating (Sec. 2), not through geometry: the stationary shape is a solution of the Euler–Lagrange equations for (1) under fixed bounds.

Euler–Lagrange form (stationarity). Let κ_k, τ_k be treated via the standard Lagrange–Rayleigh helical calculus with constraints $g(\gamma_k) = 0$ (sterics, distance, angles). Then

$$\frac{\delta \mathcal{A}}{\delta \gamma_k} \;=\; -2A\left(\kappa_k'' - \tfrac{1}{2}\kappa_k^3 - 2\tau_k^2\kappa_k\right)\mathbf{n}_k \;-\; 2C\left(2\tau_k'\kappa_k + \tau_k\kappa_k'\right)\mathbf{b}_k \;+\; \nabla_{\gamma_k}[w_{\text{dock}} J(r_{\text{dock}})] \;+\; \sum_j \lambda_j \nabla_{\gamma_k} g_j \;=\; 0,$$

with the corresponding stationarity for $\mathbf{f}_k$ aligning faces. Constant–curvature/constant–torsion solutions (circular helices) solve the homogeneous transport part; alignment terms then quantize radius/phase to satisfy the docking window.

4.2 Main Theorem (Duplex inevitability)

Theorem 4.1 (counter–wound double helix is unique minimizer). *Among all admissible codes obeying Sec. 3 constraints and the RS gate policy, the unique stationary minimizer of* (1) *is a pair of counter–wound, coaxial helices with constant curvature κ and torsion τ, separated by a constant inter–strand distance $\delta_\star$ inside the H–bond window, and with face vectors $\mathbf{f}_1, \mathbf{f}_2$ locked antiparallel at the docking sites. The stable geometric ratios match the φ bands:*

$$G_{\min} \;\approx\; 13.6\ \text{Å}, \qquad P \;\approx\; \varphi^2 G_{\min}\ \ (\sim 34\text{–}35\ \text{Å}), \qquad \frac{G}{G_{\min}} \;\approx\; \varphi.$$

Proof sketch. (i) The transport part in (1) is minimized by constant κ, τ (Euler elastica on a rod with twist), hence a circular helix for each strand. (ii) Binding terms add a face–to–face alignment potential that fixes a phase offset between strands; minimizing $J(r_{\text{dock}})$ under the window constraints selects a *single* offset producing two unequal groove arcs (major/minor). (iii) The RS symmetry of J and the no–knob policy eliminate sequence dependence at the gate; the only continuous degrees of freedom are (R, P) of the helix (radius and pitch). (iv) Minimizing $A\kappa^2 + C\tau^2$ subject to the H–bond window and sterics gives a fixed ratio $\tau/\kappa = \tan\psi$; the RS eight–beat timing enforces a commensurability that pins $\tan\psi$ to the golden band. Translating to observables yields

$P \approx \varphi^2 G_{\min}$ and $G/G_{\min} \approx \varphi$ with a narrow tolerance set by A/C and the window. Uniqueness follows from strict convexity of the transport term and strict convexity of J in the admissible region. □

Helix identities (for reference). For a circular helix of radius R and pitch P per 2π turn,

$$\kappa = \frac{R}{R^2 + (P/2\pi)^2}, \qquad \tau = \frac{P/2\pi}{R^2 + (P/2\pi)^2}, \qquad \frac{\tau}{\kappa} = \frac{P}{2\pi R}.$$

The golden band fixes $P/(2\pi R)$ and hence both (R, P) once $\delta_\star$ and groove partition are set by docking.

4.3 Corollaries

C1 (optimal stacking angle window). The face alignment term pinches the dihedral between stacked bases to a small interval $[\theta_-, \theta_+]$ around the elastica optimum; outside this window the ledger penalty steepens (convex J), predicting a sharp drop in stability.

C2 (bend persistence). Linearization about the stationary helix gives a quadratic bending Hamiltonian with persistence length

$$\ell_p \;\approx\; \frac{A_{\text{eff}}}{k_B T},$$

where A_{eff} is the second variation of the transport term evaluated at (κ, τ) selected by the golden band; ℓ_p thus inherits weak temperature and solvent dependencies through A_{eff} only.

C3 (tolerance bands). Finite H–bond windows and sterics induce narrow tolerances:

$$\frac{P}{\varphi^2 G_{\min}} \in [1 - \epsilon_P,\ 1 + \epsilon_P], \qquad \frac{G}{\varphi G_{\min}} \in [1 - \epsilon_G,\ 1 + \epsilon_G],$$

with ϵ_P, ϵ_G of order a few percent set by $(d_{\min}, d_{\max}, \alpha_{\max}, \beta_{\max})$ and A/C.

4.4 No–go (geometry)

Proposition 4.2 (non–duplex codes are suboptimal under φ timing). *Any non–duplex code (planar ladders, parallel ribbons without counter–winding, or multistrand bundles without complementary face locking) cannot simultaneously (i) minimize the transport part of* (1) *under the steric window and (ii) achieve a stable face–to–face docking ledger minimum across φ–timed gates.*

Sketch. Planar/ladder geometries force alternating regions of high curvature or torsion to satisfy sterics and docking, raising $A\kappa^2 + C\tau^2$ versus the circular–helix baseline; bundles induce unavoidable face frustration (no global antiparallel lock) that increases $J(r_{\text{dock}})$ at gate. Under the RS gate's symmetry and no–knob policy, these penalties cannot be tuned away, so the duplex dominates.

4.5 Falsifier

If experiments run under the declared instrument (Sec. 2) yield *stable* winners whose fitted geometry lies *outside* the φ bands—e.g., $G/G_{\min} \notin [\varphi(1-\epsilon_G),\ \varphi(1+\epsilon_G)]$ or $P/(\varphi^2 G_{\min}) \notin [1-\epsilon_P,\ 1+\epsilon_P]$—and these winners persist after schedule/energy audits, then the duplex inevitability claim (Theorem 4.1) is rejected. The falsifier is quantitative and local: it does not depend on environmental recipes or monomer identities, only on the auditable geometry under the gate.

5 Energetics and Scheduling

5.1 LISTEN/LOCK/BALANCE

We partition each control period T into three phase groups aligned with the eight–beat φ schedule:

$$W_{\mathrm{LISTEN}}, \quad W_{\mathrm{LOCK}}, \quad W_{\mathrm{BALANCE}}, \qquad |W_{\mathrm{LISTEN}}| + |W_{\mathrm{LOCK}}| + |W_{\mathrm{BALANCE}}| = T,$$

with $|W_{\mathrm{LOCK}}|/|W_{\mathrm{LISTEN}}| \in \{\varphi, \varphi^{-1}\}$ and analogous relations between groups inherited from Sec. 2. During *LISTEN* the mid–IR drive is low (diagnostic illumination); during *LOCK* a short, bounded envelope delivers energy near the coherence band $\tilde{\nu}_{\mathrm{coh}} \approx 724\ \mathrm{cm}^{-1}$; during *BALANCE* the drive is relaxed to allow incorrect contacts to dissipate and transport to resume.

Work/heat and duty. Let $I(t)$ be the mid–IR intensity incident on the sample and $S(\tilde{\nu}, t)$ the measured spectral power density. The per–cycle energy input and lock–band occupancy are

$$E_{\mathrm{in}} = \int_0^T I(t)\, dt, \qquad \mathrm{Occ}_{724} = \frac{1}{|W_{\mathrm{LOCK}}|} \int_{W_{\mathrm{LOCK}}} S(\tilde{\nu} \approx 724\,\mathrm{cm}^{-1}, t)\, dt.$$

Ledger descent over the lock gate is $\Delta\mathcal{L} = \mathcal{L}_{\mathrm{pre}} - \mathcal{L}_{\mathrm{post}}$. We define the *energetic efficiency* of recognition as

$$\eta \;=\; \frac{\Delta\mathcal{L}}{E_{\mathrm{in}}}\,.$$

Duty–cycle design sets $(|W_{\mathrm{LISTEN}}| : |W_{\mathrm{LOCK}}| : |W_{\mathrm{BALANCE}}|)$ and window ramps (raised–cosine C^1 by default) to maximize η subject to safety bounds (dose, peak T, $\dot{T}$). Gate *noise immunity* arises from (i) $J(x)$ symmetry (equal penalty for over/under), (ii) phase averaging inside windows, and (iii) φ–separation that suppresses low–order spectral leakage (Sec. **??**).

5.2 Timing advantage

Lemma 5.1 (–gating maximizes ledger descent per unit energy). *Among schedules with identical duty, per–cycle energy E_{in}, and ramp class, the eight–phase φ schedule achieves maximal (or co–maximal) energetic efficiency $\eta = \Delta\mathcal{L}/E_{\mathrm{in}}$ within the class of band–limited plant couplings. Moreover, for co–phased or equal–spaced baselines,*

$$\frac{\Delta\mathcal{L}_{\varphi}}{E_{\mathrm{in}}} \;\geq\; \Big(1 + \sigma\Big)\, \frac{\Delta\mathcal{L}_{\mathrm{base}}}{E_{\mathrm{in}}}, \qquad \sigma \;\geq\; c\,(1-\kappa)\,\varphi^{-1} \;>\; 0,$$

where $\kappa \in (0,1)$ is the cross–interference constant of Theorem A.1 and c depends on window smoothness and surrogate sensitivities.

Proof sketch. In the near–linear regime, the incremental ledger descent is the useful signal minus cross–terms that re–excite off–target modes. The –phase interference bound (Theorem A.1) reduces the time–averaged bilinear cross–terms by a strict factor $\kappa\varphi^{-1}$ relative to co–phased/equal–spaced schedules at equal duty. With identical E_{in} and ramps, less leakage yields larger net $\Delta\mathcal{L}$; maximizing over schedules in the admissible class gives the stated efficiency ordering. □

5.3 Spectral predictions

The instrument predicts specific, phase–resolved spectral features:

1. **IR lock spike.** A transient increase in Occ_{724} during *LOCK* with ratio

$$\mathcal{R}_{\mathrm{lock}} = \frac{\mathrm{Occ}_{724}^{\mathrm{LOCK}}}{\mathrm{Occ}_{724}^{\mathrm{LISTEN}}} \;\geq\; R_{\min},$$

where $R_{\min}$ is preregistered from sensitivity calibration.

2. **Phase–dependent line shapes.** The measured spectrum is the convolution of the intrinsic line with the window envelope. C^1 (raised–cosine) windows suppress side lobes; hard edges introduce sidelobes at multiples of $2\pi/|W_{\mathrm{LOCK}}|$, degrading η (observable as broadened shoulders).

3. **Isotopic scaling (D_2O, deuterated tokens).** For a mode approximated as a harmonic oscillator,

$$\tilde{\nu}' \;\approx\; \tilde{\nu}\sqrt{\frac{\mu}{\mu'}},$$

with reduced mass μ (μ' after isotopic substitution). Predictions: a redshift of the lock band under D substitution with magnitude fixed by the local reduced–mass change; the lock spike persists if timing and dose are unchanged.

4. **Temperature scaling.** Mild, approximately linear anharmonic redshift

$$\frac{d\tilde{\nu}}{dT} \;\approx\; \alpha_T < 0 \quad \text{(small)}, \qquad \frac{d\,\mathrm{Occ}_{724}}{dT} \;\approx\; \beta_T,$$

with α_T, β_T preregistered from calibration runs; the spike amplitude decreases outside the optimal window due to broadened occupancy.

5.4 Falsifier

If *either* (i) the drive is moved off–band by a preregistered margin or (ii) the schedule is scrambled to equal–spaced/co–phased updates at equal duty, then both

$$\mathcal{R}_{\mathrm{lock}} < R_{\min} \quad \text{and} \quad \Delta\mathcal{L} < \Delta\mathcal{L}_{\min}$$

must be observed; failure of this negative control falsifies the claimed timing/energetics advantage. Conversely, under the declared instrument, absence of a lock spike and ledger drop above thresholds falsifies the gate itself. All thresholds ($R_{\min}, \Delta\mathcal{L}_{\min}$) are preregistered; outcomes are decided by pass/fail audits, not post hoc interpretation.

6 Replication as a Fixed Point

6.1 Recognition map

Let s denote the local state (two facing sites, backbone frames, solvent microstate, and contact register $\sigma \in \{\mathsf{free}, \mathsf{bind\text{-}ready}, \mathsf{locked}\}$). One φ–timed cycle (LISTEN/LOCK/BALANCE) induces a *gate kernel*

$$K_\varphi(s' \mid s)\,,$$

a Markov transition law whose control dependence enters only through the *timing envelope* and dose (Sec. 5), not through sequence. Let $\mathcal{R}$ be the recognition operator acting on observables

f by $(\mathcal{R}f)(s) = \mathbb{E}[f(s') \mid s]$ with $s' \sim K_\varphi(\cdot \mid s)$. We will use coarse *recognition ratios* $r = (r_i)_i$ (dimensionless proxies of correct vs. incorrect microstates) and write the induced map on ratios as

$$r^+ \;=\; \mathcal{R}(r)\,.$$

Under the RS *no–knob* policy, K_φ is sequence–indifferent at the gate; complement identity enters only *through geometry* (Sec. 4), so $\mathcal{R}$ is the same map for all sequences that respect the duplex constraints.

6.2 Contraction metric

Let $u = \ln r$ be log–ratio coordinates and equip the space with the weighted quadratic metric

$$d_W(u,v)^2 \;=\; \sum_i w_i\,(u_i - v_i)^2,$$

where $w_i > 0$ are the transport–sensitivity weights (Sec. 2). Denote by $u^\star$ the *complement fixed point* ($r^\star\!=\!1$).

Lemma 6.1 (local contraction). *There exist $\rho \in (0,1)$ and a neighborhood $\mathcal{N}$ of $u^\star$ such that for all $u \in \mathcal{N}$, one φ–timed gate yields*

$$\mathbb{E}\big[\,d_W\big(\,u^+, u^\star\,\big)^2 \;\big|\; u\,\big] \;\le\; \rho\, d_W\big(u, u^\star\big)^2\,.$$

Sketch. In log–ratios, the ledger $J(r_i) = \cosh(u_i) - 1$ is quadratic to second order ($J \approx \frac{1}{2}u_i^2$). The gate kernel is a small, smooth perturbation of the identity with drift aligned to $-\nabla_u \sum_i w_i J(r_i)$ (ledger descent during LOCK). Linearization and the –phase interference bound (which suppresses cross–terms) give a Jacobian with spectral radius < 1 in the W–metric. □

Corollary 6.2 (Banach fixed point ⇒ templating). *On $\mathcal{N}$, $\mathcal{R}$ admits a unique fixed point $u^\star$ and $u \mapsto \mathcal{R}(u)$ is a contraction; iterates converge geometrically to $u^\star$. Interpreting $u^\star$ as complement alignment, the cycle implements* templated copying*.*

6.3 Error bounds

Let ϵ be the per–site copying error (mismatch probability) over one cycle, and let δt be the timing mismatch from the optimal LOCK centroid within its window.

Proposition 6.3 (quadratic timing sensitivity). *For smooth (at least C^1) window edges and band–limited response, there exist $\epsilon_0 \ge 0$ and $c > 0$ such that for sufficiently small timing offsets*

$$\epsilon \;\le\; \epsilon_0 \;+\; c\,\delta t^2\,.$$

Sketch. The correct–lock transition probability attains a maximum at the optimal phase; smoothness implies a vanishing first derivative and negative second derivative there. Expanding to second order and normalizing by total attempts yields a quadratic loss; –separation prevents first–order contamination from other actuators. □

Speed–fidelity trade. Let $|W_{\text{LOCK}}| = \tau_L$ and cycle time T (throughput $\nu = 1/T$). The ledger drop $\Delta\mathcal{L}(\tau_L)$ is increasing, concave in τ_L (diminishing returns under dose caps); fidelity improves with $\Delta\mathcal{L}$ (next subsection), while throughput improves as T shrinks. Thus, for declared caps,

$$\frac{d(1-\epsilon)}{d\nu} \;\leq\; -\alpha\,\frac{d\,\Delta\mathcal{L}}{d\nu}\,,$$

with $\alpha > 0$ a calibration constant: higher speed (larger ν) generally reduces ledger drop per cycle and hence the achievable fidelity.

6.4 Fidelity floor

We now link the *measured* LOCK–phase ledger drop to a guaranteed accuracy.

Theorem 6.4 (accuracy from ledger drop). *There exist calibration constants $\kappa_f > 0$ and $\varepsilon_f \geq 0$ such that for any cycle with declared LOCK–phase ledger descent $\Delta\mathcal{L}$, the per–site copying accuracy obeys*

$$1-\epsilon \;\geq\; (1-\epsilon_0) \;+\; \kappa_f\,\Delta\mathcal{L} \;-\; \varepsilon_f\,.$$

Sketch. The gate increases the odds ratio of correct over incorrect binding by a factor that is exponential in the log–ratio drift; near the fixed point this increment is linear in u and hence in J (quadratic norm). Using the local descent lemma ($\Delta Q \propto -\Delta\mathcal{L}$ analogue) and a monotone link between odds ratio and accuracy yields the inequality with κ_f from sensitivity calibration and ε_f absorbing higher–order and tube–robustness terms. $\square$

Calibration. Estimate κ_f by measuring $(\Delta\mathcal{L}, \epsilon)$ over short episodes under –phased probes; fit a robust slope for $1-\epsilon$ vs. $\Delta\mathcal{L}$ near operating points; set ε_f to the lower one–sided confidence margin. Preregister $(\kappa_f, \varepsilon_f, \epsilon_0)$.

6.5 Falsifier

Under the declared instrument (–timed drive, coherence band, fixed thresholds), if complement copying *does not* exceed matched controls (off–band or scrambled timing) by at least the preregistered ledger margin—i.e.,

$$\big[(1-\epsilon)_{\varphi} - (1-\epsilon)_{\text{control}}\big] \;<\; \kappa_f\,\Delta\mathcal{L} - \varepsilon_f\,,$$

then the fixed–point templating claim fails. This falsifier is local, quantitative, and sequence–indifferent; it terminates the claim without recourse to recipe–specific narratives.

7 Evolvability Window

7.1 Timing jitter $\Rightarrow$ mutation

Let δt denote the deviation of the LOCK centroid from its preregistered optimal phase within the active window. For small offsets, Proposition 6.3 gives a quadratic penalty on per–site error

$$\epsilon \;\leq\; \epsilon_0 \;+\; c\,\delta t^2 \quad (+\text{ higher order}).$$

Assume phase timing jitter is exogenous and zero–mean with variance σ_t^2 and finite fourth moment $\mu_4 = \mathbb{E}[\delta t^4]$. Then, to leading order (delta method),

$$\begin{aligned}
\mathbb{E}[\epsilon] \;&\approx\; \epsilon_0 \;+\; c\,\mathbb{E}[\delta t^2] \;=\; \epsilon_0 \;+\; c\,\sigma_t^2, \\
\mathrm{Var}[\epsilon] \;&\approx\; c^2\,\mathrm{Var}[\delta t^2] \;=\; c^2\,(\mu_4 - \sigma_t^4)\begin{cases} 2c^2\sigma_t^4 & \text{if } \delta t \sim \mathcal{N}(0,\sigma_t^2), \\ \text{use } \mu_4 \text{ otherwise.} \end{cases}
\end{aligned}$$

Bias structure (transition vs. transversion analogues). Let the docking tolerance be anisotropic: acceptance volumes differ for "in–class" vs. "cross–class" mismatches. Writing angular/distance windows as $(\Delta\alpha, \Delta\beta, \Delta\delta)$, the ratio of class–conditional error propensities is predicted by acceptance–volume ratios,

$$\frac{p_{\mathrm{in}}}{p_{\mathrm{cross}}} \;\approx\; \frac{\Delta\alpha_{\mathrm{in}}\Delta\beta_{\mathrm{in}}\Delta\delta_{\mathrm{in}}}{\Delta\alpha_{\mathrm{cross}}\Delta\beta_{\mathrm{cross}}\Delta\delta_{\mathrm{cross}}},$$

hence a *bias* toward the class with looser geometric tolerances under identical timing jitter. For canonical nucleotides this predicts a "transition > transversion" tendency; for other chemistries compute from the measured docking anisotropy.

7.2 Selection

Environmental changes (solvent, temperature, cofactors) perturb sensitivities and thus the weights w_i and/or targets $y_i^\star$, yielding variant–specific ledger drops $\Delta\mathcal{L}_g$ and error rates ϵ_g. Define a fitness proxy per cycle

$$f_g \;=\; \kappa_{\mathrm{sel}}\,\Delta\mathcal{L}_g \;-\; \lambda_{\mathrm{err}}\,\epsilon_g,$$

with positive calibration constants $(\kappa_{\mathrm{sel}}, \lambda_{\mathrm{err}})$ (declared). Variant frequencies x_g then follow a replicator equation

$$x_g^{(t+1)} \;=\; \frac{x_g^{(t)}\,e^{\,f_g}}{\sum_h x_h^{(t)}\,e^{\,f_h}} \quad\Longrightarrow\quad \Delta x_g \approx x_g\,(f_g - \bar{f}) \quad \text{for small } f,$$

so *differential ledger descent* acts as selection strength modulated by fidelity costs. This makes $\Delta\mathcal{L}$ both a control objective and an evolutionary proxy.

7.3 Phase diagram

Let D be a dimensionless drive parameter (e.g., normalized energy per cycle E_{in}/E_0 or duty–adjusted lock dose) and let $\rho_L = |W_{\mathrm{LOCK}}|/T$ be the lock duty. Using Secs. 5–6, the regime boundaries are:

No replication: $\mathrm{Occ}_{724} < \Theta_{\mathrm{spec}}$ or $\Delta\mathcal{L} < \Lambda$ (gate fails; below dose/geometry thresholds).

Life–like: $\mathrm{Occ}_{724} \ge \Theta_{\mathrm{spec}},\ \Delta\mathcal{L} \ge \Lambda,\ \epsilon \le \epsilon_c(L,\sigma)$ (fixed point holds; bounded errors).

Error catastrophe: $\epsilon > \epsilon_c(L,\sigma)$ or certificate fails (overdrive broadening).

Here ϵ_c is a quasispecies–style threshold depending on effective genome length L and selective superiority σ:

$$(1-\epsilon)^L \;>\; \sigma^{-1} \quad\Longleftrightarrow\quad \epsilon \;<\; \epsilon_c(L,\sigma) \;:=\; 1 - \sigma^{-1/L}.$$

Using the fidelity floor (Theorem 6.4) and jitter model (Sec. 7.1), an operational approximation is

$$\epsilon(D,\sigma_t^2) \;\lesssim\; \epsilon_0 \;+\; c\,\sigma_t^2 \;-\; \kappa_f\,\Delta\mathcal{L}(D,\rho_L) \;+\; \varepsilon_f,$$

so the life–like band is the locus where the right–hand side stays below ϵ_c while certificate thresholds are met. Empirically, $\Delta\mathcal{L}$ increases then saturates with D (dose capped), while excessive D broadens line shapes and can raise ϵ (off–target stabilization), shrinking the safe band—hence a *dome–shaped* feasible region in (D, ρ_L).

7.4 Falsifier

With jitter statistics preregistered (distribution and σ_t^2) and sensitivity c calibrated, the model predicts

$$\mathrm{Var}[\epsilon] \;\approx\; c^2\,(\mu_4 - \sigma_t^4) \quad \text{(Gaussian: } 2c^2\sigma_t^4\text{)}.$$

If measured mutation *variance* lies outside the predicted band, or if the mean error fails the bound $\mathbb{E}[\epsilon] \le \epsilon_0 + c\sigma_t^2$ under declared conditions, the evolvability–window claim fails. Likewise, if the phase diagram's life–like region is not reproducible under fixed $(\Theta_{\text{spec}}, \Lambda, \kappa_f, \varepsilon_f)$ and (D, ρ_L, σ_t^2), the window is rejected. All outcomes are decided by the preregistered audits and confidence bands.

8 Minimal Metabolic Closure

8.1 Gradient coupling

We couple the recognition gate to a minimal energy supply composed of a synchronized proton/electron flow. Let the electrochemical potentials be

$$\Delta\mu_{\mathrm{H}^+} \;=\; F\,\Delta\Psi \;-\; RT\ln(10)\,\Delta\mathrm{pH}, \qquad \Delta\mu_{e^-} \;=\; F\,\Delta\Psi_e,$$

with Faraday constant F, membrane (or interfacial) potentials $\Delta\Psi$ and $\Delta\Psi_e$, temperature T. The –*timed* drive gates these gradients over the eight windows:

LISTEN: baseline bias (leak compensation); LOCK: brief redox push to favor correct ligation; BALANCE: prote

Denote the per–cycle particle counts admitted by the certificate as n_{H^+}, n_{e^-}, and the coupling efficiency (chemistry to ledger–relevant work) as $\eta_{\text{coup}} \in (0, 1]$. The *available gradient work per cycle* is

$$W_{\text{grad}} \;=\; \eta_{\text{coup}}\Big(n_{\mathrm{H}^+}\,\Delta\mu_{\mathrm{H}^+} \;+\; n_{e^-}\,\Delta\mu_{e^-}\Big). \tag{2}$$

8.2 Viability inequality

Let the per–cycle recognition/templating ledger drop be $\Delta\mathcal{L}$ and the calibrated energy quantum for lock events be $E_{\text{coh}} \approx 0.09$ eV (Sec. 2). Write the *required work per cycle* as

$$W_{\text{req}} \;=\; W_{\text{rec}} \;+\; W_{\text{lig}} \;+\; W_{\text{exp}},$$

where $W_{\text{rec}} \approx N_{\text{lock}}\,E_{\text{coh}}$ (number of lock events N_{lock}), W_{lig} covers activation for covalent joins (reduced by catalysis), and W_{exp} is waste export (osmotic/entropic). A conservative proxy uses the measured ledger drop with a calibration factor $\chi_E > 0$:

$$W_{\text{rec}} \;\ge\; \chi_E\,\Delta\mathcal{L}\,.$$

Viability inequality (closure):

$$W_{\text{grad}} \;\ge\; W_{\text{req}} \quad\Longleftrightarrow\quad \eta_{\text{coup}}\Big(n_{\mathrm{H}^+}\,\Delta\mu_{\mathrm{H}^+} + n_{e^-}\,\Delta\mu_{e^-}\Big) \;\ge\; \chi_E\,\Delta\mathcal{L} \;+\; W_{\text{lig}} \;+\; W_{\text{exp}}\,. \tag{3}$$

All terms are phase–gated: redox bias aligns to LOCK (favor correct ligation); proton motive force aligns to BALANCE (drive export), with per–phase caps enforced by the certificate (dose, temperature, safety).

8.3 Sustained operation

We declare *autonomous copying* when, under steady –timed IR and steady gradients:

1. **Throughput:** copy rate $\nu \geq \nu_{\min}$ sustained for $T_{\text{sustain}} \geq T_{\min}$ without external reagent pulsing beyond the scheduled drives.

2. **Certificate:** pass rate $\geq p_{\min}$ over M–window aggregations; lock–band spike and ledger margin remain above thresholds.

3. **Fidelity:** per–site error obeys the fidelity floor (Thm. 6.4) with declared $(\kappa_f, \varepsilon_f)$; no drift beyond bands.

4. **Waste:** concentrations of declared byproducts remain $\leq C_{\max}$ with bounded variance; export events occur in BALANCE windows as scheduled.

5. **Gradient health:** $\Delta\mu_{\text{H}^+}, \Delta\mu_{e^-}$ stay within preregistered bands; no cumulative depletion beyond tolerance.

Benchmarks report $(\nu,\ \mathsf{Pass},\ 1-\epsilon,\ C_{\text{waste}},\ \Delta\mu)$ as window–level signed metrics; sustained operation is a pass only if all five criteria hold simultaneously for the full $T_{\min}$.

8.4 Falsifier

With gradients fixed to preregistered bands and recognition success established (lock spike and $\Delta\mathcal{L} \geq \Lambda$), *failure* to satisfy (3)—manifested as any of:

$$\nu < \nu_{\min} \quad \text{(stall)}, \qquad \mathsf{Pass} < p_{\min} \quad \text{(gate collapse)}, \qquad C_{\text{waste}} > C_{\max} \quad \text{(export failure)}, \qquad \Delta\mu \text{ drift } \notin \text{bands},$$

over the preregistered horizon $T_{\min}$—falsifies *metabolic closure* under the declared instrument. The verdict is audit–based and local: it does not depend on environmental recipes; only on –timed coupling, measured gradients, and the signed certificate logs.

9 Cross–Chemistry Universality

9.1 Class definition

A polymer class $\mathcal{C}$ is *eligible* for RS–instrument universality if its monomers/backbone satisfy three structural criteria:

Backbone stiffness. There exist mesoscopic moduli $(A_{\mathcal{C}}, C_{\mathcal{C}})$ (bend/twist) that admit a constant–curvature/constant–torsion helix within the steric window (Sec. **??**). Operationally: the class supports a circular–helix solution with radius R and pitch P that respect excluded volume and docking distance.

Complementary faces. Each monomer presents a directed face (or face pair) with angular/distance tolerances $(\Delta\alpha, \Delta\beta, \Delta\delta)$ enabling antiparallel docking; the acceptance volume is nonzero and sequence–indifferent at the LOCK gate.

IR coupling. There is a vibrational mode (or narrow cluster) with appreciable absorption cross–section in the mid–IR near the recognition band. We declare a universal acceptance window

$$\tilde{\nu}_{\text{coh}} \in [720, 730]\ \text{cm}^{-1}$$

and accept isotopic/chemical shifts predicted by reduced–mass scaling (Sec. 5).

9.2 Cases

Canonical nucleotides (DNA/RNA). Pass expected. B–like duplex satisfies (A, C) and face constraints; lock band present; φ geometry bands predicted (Sec. **??**). RNA may prefer A–form under given solvent; still duplex with major/minor ratio within tolerance.

PNA/TNA/GNA. PNA (peptide backbone, neutral): higher stiffness; strong face complementarity; predicted tighter tolerance bands and modest blueshift/narrowing of the lock line; duplex passes with slightly altered R, P but $\rho_{/\min} \approx \varphi$ remains. TNA/GNA (alternative sugars): reduced helical radius with pitch scaling that keeps $P/(\varphi^2 G_{\min})$ within bands if faces are preserved.

Peptide–nucleic hybrids. Mixed backbones with nucleotide–like faces: pass if hybrid maintains antiparallel face registry; expect broader BALANCE dispersion (higher W_{exp}), but geometry bands hold; lock spike smaller than PNA/DNA at equal dose.

Mineral–templated polymers. Surface–assisted assembly (mica/silicate): *conditional*. If the surface enforces 2D ladders (no counter–winding), the no–go (Sec. **??**) predicts failure; if the surface serves only as a weak anisotropic scaffold (allows out–of–plane twist), duplex remains optimal and passes. Expect attenuated lock spike due to substrate damping.

9.3 Universality test

Protocol (same gate, same audits, no knobs).

1. **Gate:** identical eight–beat φ schedule, identical mid–IR envelopes (intensity/duty), identical LISTEN/LOCK/BALANCE timing; jitter budgets fixed.
2. **Audits:** same certificate thresholds: geometry bands $(P, G_{\min}, G, \rho_{/\min})$, lock occupancy $\text{Occ}_{724} \geq \Theta_{\text{spec}}$, ledger margin $\Delta\mathcal{L} \geq \Lambda$, and safety bounds (dose/T).
3. **No knobs:** no per–sequence/per–species tuning of timing, thresholds, or objective; only *global* safety limits (e.g., dose cap) may differ across classes if mandated by materials constraints (declared a priori).
4. **Outcomes:**
   - *Pass (universality affirmed):* duplex geometry within φ bands; lock spike; $\Delta\mathcal{L} \geq \Lambda$; templating with fidelity floor (Thm. 6.4).
   - *Fail (class–specific deficiency):* absence of any audit criterion *without* violating safety caps.

Predictions per class (under identical gate).

- DNA/RNA: Pass; $\mathcal{R}_{\text{lock}}$ large; $\Delta\mathcal{L}$ saturates smoothly with dose; geometry within $\pm$ few %.
- PNA: Pass; stronger lock (higher $\mathcal{R}_{\text{lock}}$) at equal dose; narrower tolerance bands; slightly shifted line shape.
- TNA/GNA: Pass if faces preserved; smaller R, adjusted P; ratios within bands; moderate lock amplitude.
- Peptide–nucleic hybrids: Pass with increased W_{exp}; certificate still satisfied; modestly lower throughput ν at equal dose.
- Mineral–templated 2D ladders: Fail (no duplex); ledger penalty rises during BALANCE; geometry outside bands.

9.4 Falsifier

If *any* non–duplex class, driven under the declared instrument (same gate, same audits, no knobs), (i) *wins the ledger* (achieves $\Delta\mathcal{L} \geq \Lambda$ with certificate pass) *or* (ii) achieves sustained templating *without* complementary faces, then the RS *exclusivity* claim fails. Conversely, if a duplex–capable class systematically *cannot* meet the geometry bands and lock/ledger thresholds despite safety–compliant dose and timing, universality is rejected for that class. Decisions are made by the preregistered certificate, not post hoc interpretation.

10 Chirality Emergence

10.1 Mechanism

We consider achiral (or racemic) precursors on a weakly anisotropic surface (or field) that breaks mirror symmetry through a small, signed parameter Δ_χ (e.g., handed step edges, screw dislocations, circularly–polarized near–field). The eight–beat φ–timed gate modulates docking/undocking so that the signed anisotropy *coherently* accumulates during LOCK while dissipating during BALANCE. Let p_L, p_D be the per–cycle probabilities that a nascent contact proceeds to a *correct* locked state for the left– and right–handed enantiomers. The surface anisotropy adds a small energetic skew $\delta E_\chi = \Delta_\chi \, \Xi$ to the lock channel (with $\Xi > 0$ a declared coupling), so that

$$p_L \;=\; p_0 \, e^{+\delta E_\chi / k_B T}, \qquad p_D \;=\; p_0 \, e^{-\delta E_\chi / k_B T},$$

up to higher–order corrections suppressed by the –phase interference bound. Because the gating is periodic and phase–coherent, the small bias does not average to zero; it compounds geometrically across cycles.

10.2 Theorem (lower bound on enantiomeric excess growth)

Let $n_L^{(t)}, n_D^{(t)}$ be the counts of correctly locked left/right products after cycle t, and define enantiomeric excess

$$\text{ee}^{(t)} \;=\; \frac{n_L^{(t)} - n_D^{(t)}}{n_L^{(t)} + n_D^{(t)}}\,.$$

Assume: (i) the LOCK window and dose satisfy the certificate (Sec. 5); (ii) per–cycle attempts $N^{(t)}$ are ϕ–gated and bounded away from 0; (iii) the anisotropy is small, so $\sinh(x) \approx x$ to first order at $x = \delta E_\chi / k_B T$. Then there exists a calibration constant $\gamma_\chi > 0$ depending on $N^{(t)}$ and the lock acceptance, such that for all cycles with certificate Pass

$$\mathrm{ee}^{(t+1)} \; - \; \mathrm{ee}^{(t)} \; \geq \; \gamma_\chi \, \frac{\delta E_\chi}{k_B T} \; - \; \varepsilon_\chi \; = \; \gamma_\chi \, \frac{\Delta_\chi \, \Xi}{k_B T} \; - \; \varepsilon_\chi \,, \tag{4}$$

where $\varepsilon_\chi \geq 0$ absorbs higher–order, jitter, and counting–noise terms (preregistered as a slack). Consequently, over m certified cycles,

$$\mathrm{ee}^{(t+m)} \; \geq \; \mathrm{ee}^{(t)} \; + \; m\Big(\gamma_\chi \, \frac{\Delta_\chi \, \Xi}{k_B T} - \varepsilon_\chi\Big) \, .$$

Sketch. Under –gating, cross–interference terms that would mix the chiral channels are suppressed (Theorem A.1). With $N^{(t)}$ attempts per cycle, the expected increments satisfy $\mathbb{E}[\Delta n_{L,D}] = N^{(t)} p_{L,D}$ and thus $\mathbb{E}[\Delta \mathrm{ee}] \approx \frac{N^{(t)}(p_L - p_D)}{N^{(t)}(p_L + p_D)} \approx \frac{\sinh(\delta E_\chi / k_B T)}{\cosh(\delta E_\chi / k_B T)} \approx \delta E_\chi / k_B T$ to first order. The prefactor γ_χ collects acceptance and duty; robustness slack ε_χ comes from finite–sample and higher–order terms. □

10.3 Proxies

Circular dichroism (CD) vs. phase. Measure CD at diagnostic wavelengths (or Raman optical activity) phase–resolved over the eight windows. Prediction: a *locked* phase lead/lag between CD and the lock–band occupancy that tracks Δ_χ; the CD amplitude grows linearly with cycle count in the small–bias regime consistent with (4).

Geometry shifts. Minor adjustments in groove asymmetry and helical twist (sub–percent) correlate with the sign of Δ_χ due to surface–induced torque; these appear as systematic shifts in fitted $(P, G, G_{\min})$ within the tolerance bands of Sec. **??**.

Ledger asymmetry. A small, signed difference in LOCK–phase ledger drop between mirror preparations, $\Delta\mathcal{L}_L - \Delta\mathcal{L}_D \propto \delta E_\chi$, serves as a controller–level proxy even before bulk composition noticeably drifts.

10.4 Falsifier

Preregister $(\Delta_\chi, \Xi, k_B T, \gamma_\chi, \varepsilon_\chi)$ and the –timed gate. If, under certified operation,

$$\mathrm{ee}^{(t+m)} - \mathrm{ee}^{(t)} \; < \; m\Big(\gamma_\chi \, \tfrac{\Delta_\chi \, \Xi}{k_B T} - \varepsilon_\chi\Big) \quad \text{for multiple } m \text{ in a planned range,}$$

or the phase–resolved CD and ledger asymmetry show no signed response to Δ_χ within bands, then the chirality–emergence mechanism is rejected under the RS instrument. Negative controls (off–band drive; scrambled timing) must also erase any apparent bias; failure to do so falsifies the instrument specificity.

11 Instrument Engineering (safe and reproducible)

11.1 φ–timed IR driver

Source and modulation. A mid–IR source (QCL or OPO; linewidth $<2\ \mathrm{cm}^{-1}$) centered in the coherence window $\tilde{\nu}_{\mathrm{coh}} \in [720, 730]\ \mathrm{cm}^{-1}$ is amplitude–modulated by an AOM/EOM under FPGA timing. Window envelopes on W_ℓ are C^1 raised–cosine by default,

$$a_\ell(t) \;=\; A_\ell \begin{cases} \frac{1}{2}\Big[1-\cos\big(\pi(t-t_\ell)/\tau_{\mathrm{ramp}}\big)\Big], & t\in[t_\ell,\, t_\ell+\tau_{\mathrm{ramp}}],\\ 1, & t\in[t_\ell+\tau_{\mathrm{ramp}},\, t_{\ell+1}-\tau_{\mathrm{ramp}}],\\ \frac{1}{2}\Big[1-\cos\big(\pi(t_{\ell+1}-t)/\tau_{\mathrm{ramp}}\big)\Big], & t\in[t_{\ell+1}-\tau_{\mathrm{ramp}},\, t_{\ell+1}], \end{cases}$$

with $\tau_{\mathrm{ramp}} \ll \Delta t_\ell$. Spectral centering uses a narrowband etalon or software–locked FTIR feedback.

Accuracy and jitter budgets. Edge timestamps (t_ℓ) satisfy

$$|t_\ell - \hat{t}_\ell| \;\le\; \varepsilon_j, \qquad \varepsilon_j/T \;\le\; \varepsilon_{\mathrm{rel}} \text{ (e.g. } 10^{-3}),$$

verified by a fast photodiode at the sample. Inter–window ratios obey $\Delta t_{\ell+1}/\Delta t_\ell \in \{\varphi, \varphi^{-1}\} \pm \varepsilon_\varphi$ with $\varepsilon_\varphi \ll 10^{-3}$.

Dose control and envelopes. Per–cycle energy

$$E_{\mathrm{in}} = \int_0^T I_0\, a_{\ell(t)}(t)\, dt$$

is held within $\pm 2\%$ by inline power metering (thermopile + MCT feedback). LISTEN/LOCK/BALANCE duty $(\rho_{\mathrm{LSN}}, \rho_{\mathrm{LCK}}, \rho_{\mathrm{BAL}})$ is fixed a priori and hash–committed.

Calibration logs. Each run emits a signed record: wavelength setpoint, instantaneous spectrum, E_{in}, (t_ℓ), (Δt_ℓ), jitter ε_j, and envelope parameters $(A_\ell, \tau_{\mathrm{ramp}})$. Records are hash–chained and cross–checked against the compliance log (Sec. **??** analogue).

11.2 Compartments and surfaces

Emulsions and vesicles. Water–in–oil emulsions ($R \sim 10$–$100\ \mu$m) or lipid vesicles ($R \sim 1$–$20\ \mu$m) provide isolated reaction volumes. Residence–time distributions $\mathcal{R}(\tau)$ are tuned by flow and geometry so that most encounters align with W_{LOCK} and export aligns with W_{BALANCE}.

Residence–time control. Microfluidic serpentine channels (Péclet $Pe \gg 1$) and constrictions create deterministic spacing; valve timing is slaved to the –scheduler to enforce arrival windows with spread $\sigma_\tau \ll \min_\ell \Delta t_\ell$.

Mineral films and anisotropy. Mica/silicate films or chiral step–edge surfaces can be introduced for templating or chirality experiments (Sec. 10). Surface coverage is kept in the dilute regime to avoid collective heating; near–field enhancement (optional metasurface) is power–limited and phase–locked to W_{LOCK}.

11.3 Measurement stack

Time–resolved IR. MCT detector + step–scan FTIR (or QCL–photothermal) provides $\mathrm{Occ}_{724}(t)$. Acquisition is window–triggered; integration over W_{LOCK} yields the lock metric.

Geometry: AFM/cryo–EM. Fixed samples (glutaraldehyde–safe variants for analog chemistries) are imaged to extract pitch P, groove widths $(G_{\min}, G)$, and ratio $\rho_{/\min}$; fits are registered with window–level logs.

Sequencing / mass spec. For chemistries supporting it, short–read sequencing or high–resolution MS validates copying outcomes and error spectra; results are linked to window indices.

Minimal signed metrics. Per window: {phase ℓ, $t_{\text{begin/end}}$, ϕ–ratio ok, E_{in}, Occ_{724}, $\mathcal{L}$, $\mathcal{A}$, Pass/Modify/Reject} with signature and previous–hash. Raw waveforms stay local; summaries suffice for conformance.

11.4 Safety

Containment. Operate in enclosed microfluidic systems with HEPA–filtered exhaust; all effluent passes through UV/heat–kill and chemical quench. No live organisms or pathogenic agents are used; polymers are non–coding analogs unless explicitly approved.

Nutritional dependencies and kill switches. Replicators require external –timed IR and gated redox; without the driver they stall. Additional dependencies (labile linkers cleaved by visible/UV, cofactor starvation) provide orthogonal kills.

Reagent choices. Prefer non–toxic monomers/backbones and inert oils/surfactants; avoid volatile organics at IR bands. Waste streams are characterized and neutralized (pH, redox).

Governance and logging. Certificate thresholds, masks, and timing are hash–committed; all hardware interlocks (over–dose, over–temp, valve faults) trip to Reject and log signed events. A safety checklist (materials, containment, disposal) is completed and archived with every campaign.

12 Experimental Program (pre–registered)

12.1 Stage I: Recognition

Goal. Demonstrate the *instrument signature* absent templating: a lock–band spike and duplex φ–geometry under the declared gate.
Protocol. Drive samples with the eight–beat φ schedule and mid–IR envelopes (Sec. 5); enforce LISTEN/LOCK/BALANCE timing and dose caps; *disable ligation* (e.g., omit activators or use nonreactive linkers).
Audits. (i) Lock occupancy $\text{Occ}_{724} \geq \Theta_{\text{spec}}$ during LOCK with ratio $\mathcal{R}_{\text{lock}} \geq R_{\min}$; (ii) fitted duplex geometry in φ bands (Sec. **??**); (iii) certificate Pass rate $\geq p_{\min}$; (iv) no templated products above noise (sequencing/MS).

12.2 Stage II: Templating

Goal. Establish templated copying on short templates with a *ledger margin* versus baselines and quantify the error spectrum.
Protocol. Enable ligation/extension chemistry under the same gate. Use short templates (few tens of sites) to simplify analysis.
Audits. (i) $\Delta\mathcal{L} \geq \Lambda$ aggregated over M windows; (ii) fidelity obeys the *fidelity floor* $1 - \epsilon \geq$

$(1-\epsilon_0)+\kappa_f\Delta\mathcal{L}-\varepsilon_f$; (iii) error spectrum within predicted bias bands (Sec. 7); (iv) negative controls (off–band, scrambled timing) fail to meet thresholds.

12.3 Stage III: Autocatalysis

Goal. Close a minimal metabolism loop and achieve *sustained* autonomous copying with adaptation under gentle drift.
Protocol. Add synchronized proton/electron gradients per Sec. 8; run for $T_{\min}$ under steady gate. Introduce preregistered drifts (temperature or solvent) within safety bands.
Audits. (i) Viability inequality (3) holds over the run; (ii) throughput $\nu \geq \nu_{\min}$, certificate $\mathsf{Pass} \geq p_{\min}$; (iii) fidelity remains above floor; (iv) waste below $C_{\max}$; (v) adaptation: variant frequencies shift per fitness proxy (Sec. 7.2) without exceeding error catastrophe.

12.4 Stage IV: Universality

Goal. Test the *same* instrument and audits across polymer classes (Sec. 9).
Protocol. Repeat Stages I–III for: canonical nucleotides; PNA/TNA/GNA analogs; peptide–nucleic hybrids; mineral–templated polymers (where applicable). *No knobs:* timing, thresholds, and objectives unchanged; only materials safety caps differ if mandated (declared a priori).
Audits. Verdict per class: Pass if geometry in φ bands, lock spike present, ledger margin met, and templating/fidelity floor achieved; Fail otherwise.

12.5 Design

Block structure. AB/BA randomized blocks where $\mathbf{A}=\varphi$–gated instrument and $\mathbf{B}=$ (baseline): (i) off–band envelopes; (ii) scrambled timing (equal–spaced/co–phased); (iii) MSE objective (same constraints). Blocks are sufficiently long to stabilize window–level metrics; invalidated blocks (trips) are replaced from a preregistered list.
Fixed masks & error models. One set of time masks per diagnostic family; robust filters (Huber/biweight) and uncertainty models are *fixed* for all arms.
Actuation parity. Total dose and duty matched within $\pm 2\%$ between A and B; identical LISTEN/BALANCE durations; identical dwell/slew and jitter budgets.

12.6 Endpoints

Primary (per stage).

- **Stage I:** $\mathcal{R}_{\text{lock}} \geq R_{\min}$ and geometry ratios in band with one–sided 95% CI above thresholds.
- **Stage II:** $\Delta\mathcal{L} \geq \Lambda$ and $1-\epsilon \geq (1-\epsilon_0)+\kappa_f\Delta\mathcal{L}-\varepsilon_f$; superiority over baselines.
- **Stage III:** closure ((3)) and sustained throughput $\nu \geq \nu_{\min}$ with $\mathsf{Pass} \geq p_{\min}$.
- **Stage IV:** universality verdict per class per Sec. 9.

Secondary. Certificate Pass/Modify/Reject rates; filter interventions; waste metrics; mutation variance vs. jitter prediction; adaptation slopes.
Acceptance bands. Thresholds (Θ_{spec}, $R_{\min}$, Λ, κ_f, ε_f, $\nu_{\min}$, $p_{\min}$) and CI methods (percentile bootstrap) are preregistered.
Power/duration. Effect sizes and CI widths are computed from pilot/surrogate data and hash–committed before execution to set block counts N_{blocks}, windows per block, and total runtime.

12.7 Data policy

Preregistration. Instrument parameters, thresholds, masks, analysis code, and acceptance bands are versioned and hash–committed; any change spawns a new version and cool–down period.
Signed compliance logs. Each window produces a cryptographically signed record (–adherence, dwell/slew/jitter flags, dose, Occ_{724}, $\mathcal{L}$, certificate vector $\mathcal{A}$, decision). Logs are hash–chained and verified by an open validator.
Open analysis code. Deterministic scripts regenerate figures and endpoint reports from the signed logs and downsampled ratio streams; reruns must match file hashes.
Privacy–preserving releases. Raw high–rate signals remain onsite; released artifacts include: (i) signed logs, (ii) downsampled ratio summaries, (iii) endpoint values with CIs, (iv) preregistration bundle, and (v) validator outputs. Independent labs can reproduce verdicts without access to sensitive waveforms.

13 LNAL: Ledger–Native AI Co–Design

13.1 Model

Goal. Co–design *materials* (monomers/backbones, faces) and *instrument schedules* (mid–IR envelopes, –timed phases) that *pass the certificate on first try*. Designs must satisfy the physics: ledger descent, –timing, and audit constraints.

Design variables. Let $z = (\theta_{\text{chem}},\ \theta_{\text{sched}},\ \theta_{\text{env}})$ collect: (i) *chemistry*: token/backbone descriptors (graphs with face normals, stiffness (A, C) proxies, IR mode parameters); (ii) *schedule*: sub–pulse amplitudes and times $\{A_k, t_k\}_{k=1}^{K}$ with $\Delta t_{k+1}/\Delta t_k \in \{\varphi, \varphi^{-1}\}$ and window ramps; (iii) *environment*: compartment sizes/residence times within bounds. A differentiable surrogate $\mathcal{S}(z)$ predicts window–level observables $\hat{r}_i$, spectrum $\hat{S}(\tilde{\nu}, t)$, and geometry $\hat{\mathcal{G}}$.

Physics–regularized objective. The *ledger–native* loss blends the RS objective with –timing and certificate terms:

$$\mathcal{L}_{\text{LNAL}}(z) \;=\; \underbrace{\mathbb{E}\Bigg[\sum_i w_i\, J(\hat{r}_i(z))\Bigg]}_{\text{ledger}} + \lambda_\varphi \underbrace{\sum_k \psi\Big(\frac{\Delta t_{k+1}}{\Delta t_k}\Big)}_{\text{–commensurability penalty}} + \lambda_{\text{cert}}\, \underbrace{\Phi_{\text{cert}}(\hat{\mathcal{G}},\ \widehat{\mathrm{Occ}}_{724},\ \Delta\hat{\mathcal{L}})}_{\text{soft certificate hinge}} + \lambda_{\text{smooth}}\, \|\nabla a(t)\|_2^2 + \lambda_{\text{dose}}\, |E$$

Here $J(x) = \frac{1}{2}(x + 1/x) - 1$; $\psi(\rho)$ penalizes deviations from $\{\varphi, \varphi^{-1}\}$ (e.g., $\psi(\rho) = \min\{(\rho-\varphi)^2, (\rho-\varphi^{-1})^2\}$); Φ_{cert} is a differentiable hinge that is 0 when geometry, lock–band occupancy, and ledger margin meet thresholds and positive otherwise; $a(t)$ is the envelope; E_{in} the per–cycle dose. Hard bounds (safety, dwell/slew) are enforced via differentiable barriers or projection layers.

Feasibility prior (KKT guidance). For schedule subproblems, add a Karush–Kuhn–Tucker residual penalty

$$\mathcal{R}_{\text{KKT}} = \big\|\nabla_{\theta_{\text{sched}}}\mathcal{L}_{\text{stage}} + \nabla c^{\top}\lambda\big\|_2^2 + \|\min(0, \lambda)\|_2^2 + \|\max(0, c)\|_2^2,$$

with c the constraint vector (–gating, dwell/slew, dose), steering solutions toward certificate–feasible optima.

13.2 Offline training

Data. Train on *certified runs only*: window–level signed logs (–adherence, dose, Occ_{724}, $\mathcal{L}$, decisions), geometry fits $(P, G_{\min}, G)$, and sequencing/MS summaries. Split by *chemistry class* to test cross–class generalization.

Surrogates and augmentation. Fit $\mathcal{S}(z)$ with physics priors: (i) geometry head constrained to helical identities (Sec. **??**); (ii) spectrum head with band–limited kernels near 724 cm^{-1}; (iii) ledger head with J built–in. Augment by *instrument–consistent* noise: timing jitter $\delta t \sim \mathcal{N}(0, \sigma_t^2)$, dose drift $\pm 2\%$, and window–edge smoothing variations; *disallow* off–band or schedule–violating augmentations.

Optimization. Minimize $\mathcal{L}_{\mathrm{LNAL}} + \beta\, \mathcal{R}_{\mathrm{KKT}}$ with Adam; gradients flow through $\mathcal{S}(z)$. Discrete elements (e.g., monomer choices) use Gumbel–softmax or straight–through estimators; schedule times use reparameterizations $t_k = t_1 + \sum_{j<k} \Delta t_j$ with $\Delta t_{j+1}/\Delta t_j = \varphi^{\sigma_j}$, $\sigma_j \in \{-1, +1\}$ relaxed during training and snapped at inference.

Safety filter at deployment. Before lab execution, a *one–step safety QP/NLP* projects the proposed schedule to the certificate–feasible set (–gated, dwell/slew, dose); infeasible designs are rejected offline.

13.3 First–try benchmarks

Metrics. *FTSR* (first–try success rate): fraction of novel designs that *pass the certificate* on their first lab run. Secondary: lock–ratio $\mathcal{R}_{\mathrm{lock}}$, ledger margin $\Delta\mathcal{L}$, fidelity $(1 - \epsilon)$ vs. floor, geometry–in–band rate, and safety violations (target: 0).

Baselines. (i) Heuristic/MSE schedule design (no ledger, equal–spaced timing). (ii) Black–box RL without physics priors (filtered for safety). (iii) Human expert schedules with matched dose.

Ablations. Remove one component at a time:

- $-J$: replace ledger head with MSE on raw diagnostics $\Rightarrow$ drop in FTSR; increased cases where $\Delta\mathcal{L}$ decreases despite "good" MSE.
- **– prior**: replace $\psi(\rho)$ with L2 on times $\Rightarrow$ degraded $\mathcal{R}_{\mathrm{lock}}$ and higher cross–term leakage; FTSR down.
- **–certificate hinge**: optimize without Φ_{cert} $\Rightarrow$ more schedule–violating proposals; higher offline rejection.

Reporting. For each chemistry class and a held–out facility configuration, report FTSR with one–sided 95% CIs, median $\Delta\mathcal{L}$, median $(1 - \epsilon)$ above floor, and violation counts. Release seeds, `configs/`, and validators so figures are exactly reproducible from signed logs.

Target. LNAL should exceed baselines on FTSR by a preregistered margin (e.g., +15–25 pp) while reducing offline rejections. Success means *fewer shots to science*: designs that meet audits with no per–trial tuning, across chemistries, under the same instrument.

14 Geophysical & Astrobiological Implications

14.1 Earth mapping

Natural φ–like duty cycles. Several terrestrial cycles approximate multi–scale duty patterns that can be segmented into φ–commensurate windows: (i) diurnal heating/cooling in arid zones (strong, repeatable low–cloud regimes); (ii) intertidal wet–dry pulses (spring/neap beats superposed on tides); (iii) convective oscillations in geothermal outflows (minutes–hours); (iv) wave–wash in supratidal zones with beat patterns set by swell and surf. These cyclicities provide LISTEN/LOCK/BALANCE–like windows without high technology; the test is whether recognition metrics (lock–band occupancy; ledger drops) rise at consistent phases.

Mid–IR windows. The lock band at $\tilde{\nu}_{\text{coh}} \approx 724\ \text{cm}^{-1}$ corresponds to $\lambda \approx 13.8\ \mu\text{m}$, inside the terrestrial 8–14 μm atmospheric window. Ground access requires *dry air* (low precipitable water) and low cloud; near–surface transmission is best in deserts, polar plateaus, and high mountain basins. Subsurface/near–field coupling can be achieved on mineral surfaces with evanescent–field probes (ATR) or metasurface concentrators tuned to the band.

Mineral scaffolds. Layered silicates (mica, montmorillonite) offer flat, low–defect terraces for duplex alignment; iron sulfides (greigite/pyrite) provide redox microenvironments; chiral quartz (α–SiO_2) and step–edge calcite furnish anisotropy for chirality experiments (§10). For each site, we pre–survey: (i) IR background; (ii) residence–time distributions (wet/dry); (iii) ionic strength and pH stability; and (iv) surface roughness/defect densities. Sites are ranked by an "instrument score" combining duty fidelity, IR access, and safety logistics.

14.2 Exoplanet predictions

Surface/atmosphere conditions. RS instrument viability favors: (i) temperature ranges allowing hydrogen–bond recognition while avoiding thermal erasure (broadly 240–330 K), (ii) mid–IR transparency windows in the 8–14 μm band (low continuum opacity from water and CO_2 near the lock line), (iii) cyclic drivers (tides, diurnal beats, seasonal desiccation) that can approximate LISTEN/LOCK/BALANCE duty. Dry, temperate desert worlds and tide–modulated littoral zones are prime.

Biosignature spectra (instrument fingerprints). Remote detection of a *narrow* feature near 13.8 μm is implausible globally, but *in situ* or close–flyby instruments can look for active responses: a phase–locked increase in local emissivity/absorption near $\sim 724\ \text{cm}^{-1}$ when a controlled envelope is applied (lander–borne IR source), plus ledger–aligned proxies (e.g., humidity/ion gradients) shifting at the gate. Macro–biosignatures remain classical (O_2/CH_4 disequilibria), but our instrument adds an *active* life test: does the chemistry *respond correctly* to a known recognition drive?

15 Related Work (surgical)

RNA world. Templating by ribonucleotides is central, but most accounts are recipe–centric and lack a unifying instrument. We differ by deriving duplex geometry and templating from a *single* ledger and timing scheme, with pass/fail audits that do not depend on specific monomers.

Metabolism–first. Autocatalytic cycles plausibly precede templating. Our closure (§8) shows when a minimal redox/proton gradient *must* be sufficient *once* recognition succeeds; viability is an inequality tied to measured ledger drops rather than a narrative.

Lipid–world. Compartmentalization aids selection and stability, but membranes alone do not provide a recognition instrument. Here, vesicles/emulsions are engineered for residence–time control to *implement* LISTEN/LOCK/BALANCE.

Mineral templates. Clays, micas, and sulfides can align or energize chemistry; without duplex inevitability and certificate gates they are uncontrolled. We quantify when surfaces help (allow twist; light coupling) vs. hinder (force planar ladders; §**??** no–go).

Autocatalytic sets & kinetic proofreading. We share the emphasis on error control and network effects, but replace bespoke kinetics with a universal ledger and timing. Proofreading here emerges as a natural consequence of the LOCK/BALANCE split and J–symmetry, with a fidelity floor (§6.4) tied to measured ledger drops.

Contrast in one line. Instrument unification, quantitative audits, and preregistered falsifiers distinguish this work from recipe–driven accounts.

16 Discussion

What success means. Stage I–IV passes (lock spike, φ geometry, templating with a fidelity floor, minimal metabolic closure, and cross–chemistry success without knobs) would demonstrate that life's core loop is a *phase of matter under a recognition instrument*. It would move abiogenesis from "lucky recipe" to "controlled physics."

What failure means. Crisp failure modes map to assumptions: (i) no lock spike $\Rightarrow$ wrong band/timing; (ii) geometry out of φ bands $\Rightarrow$ duplex inevitability false; (iii) templating without ledger margin $\Rightarrow$ fixed–point claim fails; (iv) no closure at declared gradients $\Rightarrow$ energy model wrong; (v) a non–duplex class wins the ledger $\Rightarrow$ exclusivity fails. Each failure is informative and narrows theory.

Limits. We do not claim organismal complexity or planetary histories. The fidelity floor is local and calibrated; large excursions or exotic chemistries may demand re–linearization. Remote biosignatures remain challenging; active tests are most compelling *in situ*.

Next questions. (1) Tighten the no–go theorem for non–duplex codes. (2) Quantify chirality growth across substrates and temperatures. (3) Map the full speed–fidelity–dose surface and its universality across chemistries. (4) Demonstrate on–chip metabolic closure with feedback control of gradients.

Path to a standard. Publish the open instrument spec (gate, ledger, thresholds), the validator, and round–robin protocols. Require signed compliance logs for any claim. Maintain a living registry of successful Stages I–IV by chemistry class, with independent reproductions. The field advances when claims are *portable, audited, and falsifiable*—and this instrument makes that the default.

Appendix A — No–Go Theorem: Duplex is Necessary (Stronger Necessity)

A.0 Setting and assumptions

We work under the RS instrument of this paper: the convex symmetric ledger

$$J(x) = \tfrac{1}{2}(x + 1/x) - 1, \qquad x > 0,$$

the eight–beat φ–timed schedule with band–limited couplings (Theorem A.1), the coherence quantum $E_{\mathrm{coh}} \approx 0.09$ eV, and dose/duty caps declared in the certificate. Geometry constraints are those of Sec. 3: locality, sterics, torsion/curvature bounds, and sequence–indifferent gating. The geometric action per turn is

$$\mathcal{A}[\gamma_1, \gamma_2, \mathbf{f}_1, \mathbf{f}_2] = \int_0^{\Lambda} \Big(w_{\mathrm{dock}}\, J(r_{\mathrm{dock}}) + A \sum_{k=1}^{2} \kappa_k^2 + C \sum_{k=1}^{2} \tau_k^2 + w_{\mathrm{face}}\, J(r_{\mathrm{face}}) \Big)\, ds, \tag{5}$$

with symbols as in Sec. 4. The duplex benchmark ($\star$) is the counter–wound helix minimizing (5) subject to docking windows (Theorem 4.1), achieving ledger drop $\Delta\mathcal{L}_\star$ and contraction constant $\rho_\star < 1$ (Lemma 6.1).

Non–duplex code classes. We call *non–duplex* any code lacking two antiparallel, counter–wound strands with constant (κ, τ) and global face lock. Model classes:

- **Ladder/plane**: two parallel strands with $\tau \equiv 0$ and planar rungs (no counter–winding).
- **Ribbon/parallel helix**: co–wound or parallel helices without antiparallel face locking along the full length.
- **Multistrand bundles**: $N \geq 3$ strands with frustrated face alignment (no global antiparallel registry).
- **Surface–forced 2D**: mineral lattices pinning a 2D register precluding out–of–plane twist needed for antiparallel lock.

A.1 Transport lower bound for non–duplex codes

[Transport penalty] Let $\mathcal{C}$ be any non–duplex class as above. For any admissible configuration in $\mathcal{C}$ that satisfies the docking distance/angle window on a set of positive measure, we have the strict lower bound

$$\int_0^{\Lambda} \Big(A \sum_k \kappa_k^2 + C \sum_k \tau_k^2 \Big)\, ds \;\geq\; \int_0^{\Lambda} \Big(A\, \kappa_\star^2 + C\, \tau_\star^2 \Big)\, ds \;+\; \Delta_{\mathrm{trans}}(\mathcal{C})\,,$$

with $\Delta_{\mathrm{trans}}(\mathcal{C}) > 0$ depending only on steric/torsion windows and the class $\mathcal{C}$.

Sketch. For the benchmark duplex, constant $(\kappa_\star, \tau_\star)$ minimize the quadratic transport term under sterics. In ladders ($\tau \equiv 0$), docking windows force alternating curvature segments or localized kinks to maintain distances, strictly increasing the integral. In parallel/ribbon and multistrand bundles, global antiparallel lock is impossible; satisfying local docking requires piecewise–varying (κ, τ) or out–of–phase registry, again increasing the integral by convexity. The gap is uniform because constraints are uniform and the helical elastica is the unique constant–coefficient minimizer. $\square$

A.2 Docking frustration lower bound

[Face/docking frustration] For any non–duplex class $\mathcal{C}$, the ledger terms obey

$$\int_0^\Lambda \big(w_{\text{dock}}\, J(r_{\text{dock}}) + w_{\text{face}}\, J(r_{\text{face}})\big)\, ds \;\geq\; \int_0^\Lambda \big(w_{\text{dock}}\, J(r^\star_{\text{dock}}) + w_{\text{face}}\, J(r^\star_{\text{face}})\big)\, ds \;+\; \Delta_{\text{dock}}(\mathcal{C})\,,$$

with $\Delta_{\text{dock}}(\mathcal{C}) > 0$ uniform on the admissible set under the same windows and no–knob policy.

Sketch. The duplex realizes global antiparallel face lock with constant phase offset, saturating the docking window across a turn. In non–duplex classes, either faces cannot be antiparallel globally (bundles/parallel helix), or geometry forbids simultaneous tangential and face alignment (ladder/2D). Because J is strictly convex and symmetric, any deviation from $r^\star$ on a set of positive measure raises the integral by a uniform margin determined by the window widths and face–angle tolerances. □

A.3 Energetic and timing constraints

Let E_{in} be the per–cycle energy and ρ_{LOCK} the lock duty. Certificate caps fix $E_{\text{in}} \leq E_{\max}$ and $\rho_{\text{LOCK}} \leq \rho_{\max}$. The –phase interference bound (Theorem A.1) gives a schedule–intrinsic leakage factor $\kappa \in (0,1)$. For any class $\mathcal{C}$ driven at the same $(E_{\text{in}}, \rho_{\text{LOCK}})$, the net ledger drop satisfies

$$\Delta\mathcal{L}(\mathcal{C}) \;\leq\; \Delta\mathcal{L}_\star \;-\; \underbrace{\alpha\, \Delta_{\text{dock}}(\mathcal{C})}_{\text{lost alignment}} \;-\; \underbrace{\beta\, \Delta_{\text{trans}}(\mathcal{C})}_{\text{transport penalty}} \;-\; \underbrace{\gamma\,(1-\kappa)}_{\text{extra leakage}}\,, \tag{6}$$

for positive calibration constants (α, β, γ) tying integrals to window–level ledger changes. Equality requires the duplex benchmark and zero leakage gap.

A.4 Contraction and evolvability

Recall the contraction lemma (Lemma 6.1): $u \mapsto \mathcal{R}(u)$ is a contraction near the gate with factor $\rho_\star < 1$ for the duplex. For non–duplex $\mathcal{C}$, docking frustration injects phase–dependent mixing terms in the Jacobian; the –bound suppresses but cannot eliminate them.

[Contraction degradation] For any non–duplex class $\mathcal{C}$ under the same $(E_{\text{in}}, \rho_{\text{LOCK}})$, the recognition map contraction factor obeys

$$\rho(\mathcal{C}) \;\geq\; \rho_\star \;+\; \delta_\rho(\mathcal{C})\,, \qquad \delta_\rho(\mathcal{C}) > 0,$$

with δ_ρ determined by the same frustration gaps in Lemmas 16–16 and the leakage factor $1-\kappa$.

Sketch. Linearize $\mathcal{R}$ near the gate: the Jacobian inherits negative curvature (contraction) from ledger descent along the duplex direction, and cross–terms from misaligned faces/geometry. The latter increase the spectral radius in the W–metric by a margin controlled by frustration and un–suppressed leakage. □

A.5 Main no–go theorem

[Duplex necessity] Under fixed E_{coh}, fixed duty ρ_{LOCK}, –timed gating, and certificate caps, *no* non–duplex class $\mathcal{C}$ can simultaneously:

1. minimize the ledger/transport action (5) (equivalently, match $\Delta\mathcal{L}_\star$ at equal dose/duty), *and*

2. sustain an evolvability window (contraction $\rho(\mathcal{C}) < 1$ with bounded mutation variance under declared jitter) that meets the fidelity floor and avoids error catastrophe.

Precisely, for all $\mathcal{C}$ non–duplex,

$$(\Delta\mathcal{L}(\mathcal{C}) \geq \Delta\mathcal{L}_\star) \implies \rho(\mathcal{C}) \;\geq\; 1 \;\text{ or }\; \mathbb{E}[\epsilon] > \epsilon_c,$$

and, conversely,

$$(\rho(\mathcal{C}) < 1,\; \mathbb{E}[\epsilon] \leq \epsilon_c) \implies \Delta\mathcal{L}(\mathcal{C}) \;<\; \Delta\mathcal{L}_\star - \Delta_{\min},$$

for some class–uniform margin $\Delta_{\min} > 0$.

Proof. From Lemmas 16–16 and (6), any non–duplex $\mathcal{C}$ has a strict ledger deficit $\Delta\mathcal{L}_\star - \Delta\mathcal{L}(\mathcal{C}) \geq \alpha\Delta_{\text{dock}} + \beta\Delta_{\text{trans}} + \gamma(1-\kappa) =: \Delta_{\min} > 0$ at equal dose/duty. To close this gap one must increase dose or duty, violating caps. If caps are respected, attempting to compensate by more aggressive timing increases leakage and cross–terms, degrading contraction (Lemma 16): either $\rho(\mathcal{C}) \geq 1$ (no fixed point), or, under declared jitter, the mean/variance of ϵ exceed the phase–diagram bound ϵ_c (Sec. 7). Conversely, if one tunes (within caps) to achieve $\rho(\mathcal{C}) < 1$ and $\epsilon \leq \epsilon_c$, the same gaps force a positive shortfall in $\Delta\mathcal{L}$ relative to the duplex benchmark, so the action is not minimized. Hence the two targets cannot be achieved simultaneously by any non–duplex class under the same E_{coh} and duty caps. □

A.6 Corollaries and practical test

Corollary (surface–forced 2D no–go). Any surface that enforces planar laddering (no out–of–plane twist) cannot satisfy both ledger minimization and evolvability; at best it yields local recognition without a contraction fixed point.

Corollary (bundle frustration). Multistrand bundles with incompatible face registries necessarily fail contraction or require off–cap energy/duty, leading to certificate failure.

Practical acceptance test. Run Stage II under identical gate/caps for a duplex–capable class and a non–duplex candidate (e.g., surface–forced ladder). Measure $(\Delta\mathcal{L}, \rho, \epsilon)$:

$$[\Delta\mathcal{L}_{\text{ladder}} \geq \Delta\mathcal{L}_\star] \;\Rightarrow\; \text{expect } \rho \geq 1 \text{ or } \epsilon > \epsilon_c; \quad [\rho < 1,\; \epsilon \leq \epsilon_c] \;\Rightarrow\; \Delta\mathcal{L}_{\text{ladder}} < \Delta\mathcal{L}_\star - \Delta_{\min}.$$

Either outcome satisfies the no–go. Failure of this dichotomy falsifies Theorem 16.

Appendix B — Quantitative Fidelity Floor

B.0 Goal and statement

We derive an *auditable lower bound* that links the LOCK–phase ledger drop $\Delta\mathcal{L}$ to the per–site copying *accuracy* $1-\epsilon$:

$$1-\epsilon \;\geq\; 1-\epsilon_0 \;+\; \alpha\,\Delta\mathcal{L} \;-\; \varepsilon_f\,, \tag{7}$$

for calibration constants $\epsilon_0 \in [0,1)$, $\alpha > 0$, and a robustness slack $\varepsilon_f \geq 0$ that are *fixed pre–campaign*. (Equivalently, in the user–requested template $1-\epsilon \geq 1-\epsilon_0 - \tilde{\alpha}\,\Delta\mathcal{L}$, take $\tilde{\alpha} = -\alpha \leq 0$ so that accuracy *improves* with larger $\Delta\mathcal{L}$.)

B.1 Log–odds model near the gate

Let p be the probability that a site is copied correctly in one cycle, and $\ell = \log\left(\frac{p}{1-p}\right)$ its log–odds. The LOCK gate increases ℓ by a small positive increment $\Delta\ell$ aligned with ledger descent. In a neighborhood of the fixed point (Sec. 6), the following holds.

[Log–odds gain from ledger drop] There exist $\kappa_L > 0$, $\eta \geq 0$, and a neighborhood $\mathcal{U}$ of operation such that, for all cycles operating in $\mathcal{U}$ under –gated schedules and dose caps,

$$\Delta\ell \;\; \geq \;\; \kappa_L \, \Delta\mathcal{L} \; - \; \eta \, . \tag{8}$$

Sketch. The gate kernel increases the log–ratio coordinates $u = \ln r$ along $-\nabla \sum_i w_i J(r_i)$, and $\Delta\mathcal{L} \approx \frac{1}{2}\sum_i w_i u_i^2$ locally. The correct/incorrect channel odds respond as $\Delta\ell = \nabla\ell \cdot \Delta u + O(\|\Delta u\|^2)$ with $\nabla\ell$ aligned to the same descent direction; by Cauchy–Schwarz and the –interference suppression (Theorem A.1), the projection is bounded below by a constant $\kappa_L > 0$ up to a small remainder η absorbing higher–order terms and prediction mismatch. □

B.2 From log–odds to accuracy

Accuracy is $1-\epsilon = p = \sigma(\ell)$ with $\sigma(x) = 1/(1+e^{-x})$. On a compact calibration band $\ell \in [\ell_{\min}, \ell_{\max}]$, σ is Lipschitz with slope bounded below:

$$\sigma'_{\min} \;\; := \;\; \min_{x\in[\ell_{\min},\ell_{\max}]} \sigma'(x) \;\; = \;\; \min_x \frac{e^{-x}}{(1+e^{-x})^2} \;\; \in \;\; \left(0, \tfrac{1}{4}\right].$$

Then

$$p^+ \;\; = \;\; \sigma(\ell + \Delta\ell) \;\; \geq \;\; \sigma(\ell) + \sigma'_{\min}\, \Delta\ell \;\; \geq \;\; p \;\; + \;\; \sigma'_{\min}\big(\kappa_L \, \Delta\mathcal{L} - \eta\big).$$

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Appendix C — Isotopic / Thermal Scalings as Fingerprint

C.0 Purpose

Provide a rapid, cross–lab *identity check* for the RS instrument: the LOCK–band must shift in a quantitatively predicted way (i) under H→D substitution (D_2O or site–specific deuteration) and (ii) under ±10 K temperature steps, while the –timed signature (lock spike ratio $\mathcal{R}_{\text{lock}}$ and ledger descent $\Delta\mathcal{L}$) persists.

C.1 Mode model and isotope shift

Let the LOCK mode be locally harmonic with effective stiffness k_{eff} and *effective* reduced mass μ_{eff} (the participating mass of the H–bond frame). Then

$$\tilde{\nu} \;\; = \;\; \frac{1}{2\pi c}\sqrt{\frac{k_{\text{eff}}}{\mu_{\text{eff}}}}\, , \qquad \Delta\tilde{\nu} \;\; \approx \;\; -\frac{\tilde{\nu}}{2}\,\frac{\Delta\mu_{\text{eff}}}{\mu_{\text{eff}}}\, .$$

For H→D substitution at exchangeable sites, write

$$\mu_{\text{eff}}^{(\text{D})} \;\; = \;\; \mu_{\text{eff}}^{(\text{H})} \; + \; \phi_H\,(\,m_D - m_H\,), \qquad \phi_H \in (0,1)$$

where ϕ_H is the *participation factor* of protonic mass in the mode. The predicted *exact* shift is

$$\tilde{\nu}_{\text{D}} \;\; = \;\; \tilde{\nu}_{\text{H}}\sqrt{\frac{\mu_{\text{eff}}^{(\text{H})}}{\mu_{\text{eff}}^{(\text{D})}}} \;\; = \;\; \tilde{\nu}_{\text{H}}\left(1 \; - \; \frac{1}{2}\,\frac{\phi_H\,(m_D - m_H)}{\mu_{\text{eff}}^{(\text{H})}} \; + \; O(\phi_H^2)\right). \tag{9}$$

Two–point calibration for $\phi_H/\mu_{\text{eff}}^{(\text{H})}$. Measure $\tilde{\nu}$ in H_2O and after full H/D exchange in D_2O (controls: off–band timing, equal dose). Then

$$\frac{\tilde{\nu}_{\text{D}}}{\tilde{\nu}_{\text{H}}} = \sqrt{\frac{1}{1+\phi_H\,(m_D-m_H)/\mu_{\text{eff}}^{(\text{H})}}} \implies \frac{\phi_H}{\mu_{\text{eff}}^{(\text{H})}} = \frac{1}{m_D-m_H}\Big(\frac{1}{(\tilde{\nu}_{\text{D}}/\tilde{\nu}_{\text{H}})^2}-1\Big).$$

Lock this ratio in the preregistration; (9) then predicts *exact* shifts for any partial deuteration fraction f_D:

$$\tilde{\nu}(f_D) = \tilde{\nu}_{\text{H}}\sqrt{\frac{1}{1+f_D\,\phi_H\,(m_D-m_H)/\mu_{\text{eff}}^{(\text{H})}}}.$$

C.2 Thermal coefficient

Within ±10 K around the operating point, treat anharmonic softening as linear:

$$\tilde{\nu}(T) \approx \tilde{\nu}(T_0) + \alpha_T\,(T-T_0), \qquad \alpha_T = \Big(\frac{\partial\tilde{\nu}}{\partial T}\Big)_{T_0}.$$

Calibration. Sweep T over ±5 K at fixed gate/dose; fit α_T by robust linear regression. Declare α_T (with CI) in the preregistration. Then the predicted *exact* ±10 K shifts are $\Delta\tilde{\nu} = \alpha_T(\pm 10\text{ K})$.

C.3 Fingerprint protocol and acceptance

Protocol. (i) Acquire $\tilde{\nu}_{\text{H}}$, $\mathcal{R}_{\text{lock}}$, $\Delta\mathcal{L}$ at T_0 in H_2O; (ii) replace with D_2O, confirm exchange (IR water signatures), acquire $\tilde{\nu}_{\text{D}}$, $\mathcal{R}_{\text{lock}}$, $\Delta\mathcal{L}$; (iii) step T by ±10 K in H_2O, measure $\tilde{\nu}(T_0 \pm 10\,\text{K})$.
Acceptance.

$$\Big|\tilde{\nu}_{\text{D}} - \tilde{\nu}_{\text{H}}^{\text{pred}}\Big| \le \delta_{\nu,\text{iso}}, \qquad \Big|\tilde{\nu}(T_0{\pm}10) - (\tilde{\nu}(T_0){+}\alpha_T \pm 10)\Big| \le \delta_{\nu,\text{th}},$$

with $\tilde{\nu}_{\text{H}}^{\text{pred}}$ from (9) and declared tolerances $(\delta_{\nu,\text{iso}}, \delta_{\nu,\text{th}})$ (e.g., $\le$ 0.5–1.0 cm^{-1} depending on spectrometer). In all cases $\mathcal{R}_{\text{lock}}$ and $\Delta\mathcal{L}$ must remain above thresholds. Failure of either check falsifies the instrument fingerprint.

C.4 Notes

Partial deuteration ($0 < f_D < 1$) and site–specific labeling refine ϕ_H; a three–point fit (H_2O, 50% H/D, D_2O) over–determines the model and tightens CIs. Temperature steps must respect safety limits (dose, $\dot{T}$).

Appendix D — Cross–Chemistry Demonstrations

D.0 Goal

Convert universality from theory to evidence by executing Stage II (templating) on two *orthogonal* analog families—e.g., PNA and TNA—under the *same* instrument (–schedule, envelopes, thresholds), without per–sequence knobs.

D.1 Materials and expectations

PNA (peptide nucleic acid). Neutral backbone, higher stiffness (A, C), strong complementary faces. Expect *tighter* geometry tolerances, slightly shifted line shape, and a *larger* lock ratio at equal dose.

TNA (threose nucleic acid). Alternative sugar; smaller helical radius and adjusted pitch; faces preserved. Expect geometry ratios within φ bands; moderate lock amplitude.

D.2 Protocol (same gate, same audits)

- **Gate & safety.** Identical eight–beat schedule, identical dose caps, identical LISTEN/LOCK/BALANCE partitions. Jitter budgets and ramps fixed.
- **Audits.** Same certificate thresholds: geometry bands $(P, G_{\min}, G, \rho_{/\min})$, $\mathrm{Occ}_{724} \geq \Theta_{\mathrm{spec}}$, $\Delta\mathcal{L} \geq \Lambda$, fidelity floor (Appendix 16).
- **No knobs.** No tuning of timing or thresholds per class; only material–mandated safety caps may differ (declared ex ante).

D.3 Outcomes and acceptance

Primary. For each class: (i) geometry in φ bands; (ii) lock spike $\mathcal{R}_{\mathrm{lock}} \geq R_{\min}$; (iii) ledger margin $\Delta\mathcal{L} \geq \Lambda$; (iv) fidelity at or above floor. **Secondary.** Error–spectrum bias vs. Sec. 7; $\Delta\mathcal{L}$–vs–dose curve shape. **Acceptance.** *Both* classes must pass all primary audits under the same instrument. Negative controls (off–band, scrambled timing) must *fail* in both classes.

D.4 Transfer calibration

Report $(1 - \epsilon_0, \alpha, \varepsilon_f)$ per class (Appendix 16); declare non–inferiority margins for α between classes. If PNA/TNA both pass with overlapping α–bands, it strengthens universality; if they require different α, universality still holds provided all audits pass without timing/threshold knobs.

D.5 Falsifier

If either class cannot meet *any* primary audit under the same instrument (with safety–compliant dose), universality is rejected for that class. If a non–duplex arrangement under the same gate *wins the ledger* or templates without complement faces, exclusivity fails (Sec. 9).

Appendix E — On–Chip Metabolic Closure

E.0 Goal

Design and validate a microfluidic device that sustains replication *without* manual reagent pulsing by coupling the –timed `LOCK/BALANCE` gates to a synchronized redox loop (photocatalytic or mineral). This is the decisive step from templating to *living chemistry*.

E.1 Architecture (textual block diagram)

Reactor core. A serpentine microchannel (Pe $\gg$ 1) with reaction chambers (tens of nL) where recognition and ligation occur. Mid–IR ingress (ZnSe window) is amplitude–modulated by the –scheduler.

Redox loop. Two options, both –timed:

- *Photocatalytic:* thin–film photoanode (e.g., α–Fe_2O_3) and cathode (Pt/C) under visible/near–IR illumination gated in LOCK; proton–exchange membrane (Nafion) separates half–cells. Bias pulses synchronized to LOCK; waste export assisted in BALANCE.
- *Mineral:* packed microbed of greigite/pyrite with gate–driven potential via interdigitated microelectrodes; pH micro–valves deliver –timed proton bursts; BALANCE vents promote byproduct removal.

Sensing & control. On–chip pH (ISFETs), micro–reference electrodes for $\Delta\Psi$, thermistors for T, and an inline MCT for Occ_{724}. FPGA enforces –timing, logs events, and gates redox/IR according to the certificate.

E.2 Work budget and certificate hook

Per–cycle gradient work is

$$W_{\mathrm{grad}} = \eta_{\mathrm{coup}}\Big(n_{\mathrm{H}^+}\,\Delta\mu_{\mathrm{H}^+} + n_{e^-}\,\Delta\mu_{e^-}\Big)$$

(see Eq. (2)). The certificate enforces *closure* by requiring

$$W_{\mathrm{grad}} \;\geq\; \chi_E\,\Delta\mathcal{L} \;+\; W_{\mathrm{lig}} \;+\; W_{\mathrm{exp}}$$

(inequality (3)) on M–window aggregates, with $(\eta_{\mathrm{coup}}, \chi_E)$ calibrated on–chip.

E.3 –timed gating

LOCK: IR envelope on; redox bias pulses (μs–ms) admitted; ligation favored. BALANCE: IR off; reverse–bias or flow vent open to export byproducts; pH adjusted. LISTEN: low IR probe only; gradients at baseline. All pulses are C^1–ramped to reduce spectral leakage.

E.4 Acceptance (sustained operation)

Under steady –timed IR and redox:

1. Copy rate $\nu \geq \nu_{\min}$ maintained for $T_{\min}$ (hours) without manual reagent pulses.
2. Certificate Pass rate $\geq p_{\min}$; lock ratio and $\Delta\mathcal{L}$ stay above thresholds.
3. Fidelity obeys the floor (Appendix 16) for the entire run.
4. Waste concentrations remain $\leq C_{\max}$; export events are phase–aligned.
5. Gradients remain in preregistered bands; no cumulative drift exceeding declared tolerances.

E.5 Calibration & stress

Calibration: determine $(\eta_{\mathrm{coup}}, \chi_E)$ via short–run titrations of bias amplitude; fit linear region; hash–commit values. *Stress:* step bias $\pm 10\%$, jitter $\times 2$, or reduce BALANCE duty; report how close the system runs to the closure boundary (Eq. (3)).

E.6 Safety

Enclose effluent; inline UV/thermal kill; chemical quench of redox efflux. No live organisms; kill–switch chemistry (e.g., labile linkers) enabled. All –timed pulses hard–limited by hardware.

E.7 Falsifier

If, despite recognition success (lock spike and $\Delta\mathcal{L} \geq \Lambda$), the on–chip system fails the closure inequality or cannot sustain $\nu \geq \nu_{\min}$ and Pass$\geq p_{\min}$ over $T_{\min}$, *metabolic closure* is rejected for the declared instrument. Logs must show whether failure is due to insufficient W_{grad}, excess $W_{\mathrm{lig}}/W_{\exp}$, timing errors, or leakage from –gating.