

# The Genesis Engine

## Paper IV: The Wet–Dry Cycle as the Pump of Agency

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December 27, 2025

### Abstract

We have established that agency is a topologically protected loop (DST) characterized by anticipatory synchronization (The Hinge). In this fourth paper, we address the origin problem: How does this loop form from abiotic matter? We propose that the **Wet–Dry Cycle** acts as a universal "Genesis Pump" by providing rhythmic, high-amplitude forcing. This forcing drives dissipative systems into resonance, where the **Chaperone Effect** (action minimization) selectively stabilizes phase-locked, anticipatory trajectories—bootstrapping the Hinge and the memory advantage  $\chi$  from  $\chi < 1$  to  $\chi > 1$ . We demonstrate via Dissipation-Driven Adaptation that random polymers are energetically disfavored compared to "folded" autocatalytic sets that phase-lock to the drying phase. We model this as a non-equilibrium phase transition where the control parameter is the cycling frequency  $\Omega$ . We predict that protocells emerge after  $N_c \sim 10^3$  cycles when the driving frequency matches the system's natural frequency ( $\Omega \approx \omega_0$ ).

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# 1 Introduction: The Pump of Life

The previous papers in this series described the *structure* of agency: a closed loop (Paper II) that anticipates the future (Paper III). But structures do not appear from nowhere. They require work to build.

In equilibrium thermodynamics, systems relax to the state of maximum entropy (death). To build a low-entropy DST loop, we need a source of free energy. But raw energy is not enough; a forest fire has energy, but it destroys structure. We need *ordered* energy.

We propose that the origin of life is driven by a specific, rhythmic energy source: the **Wet–Dry Cycle**. This cycle—the periodic evaporation and re-hydration of pools on the early Earth—acts as a thermodynamic pump [1]. It forces the system to oscillate, and in doing so, it selects for the only structure that can survive oscillation: the Hinge.

We distinguish three layers of logic in this proposal:

- **Empirical Setting:** The well-established prebiotic role of wet–dry cycling in promoting polymerization [1].
- **Thermodynamic Principle:** The known tendency of driven systems to adapt to external forcing to maximize dissipation (England [2]).
- **DST Hypothesis:** Our specific claim that this environment selects for the *topological soliton* (Hinge) because the Action Kernel penalizes the "jerk" of reactive folding.

## Core Claims of Paper IV

- **Forced Resonance:** Rhythmic environmental driving forces matter to organize into cycles that match the drive frequency.
- **Selection for Anticipation:** Only systems that “predict” the drying phase (by folding/protecting) survive the stress.
- **The Genesis Engine:** The wet–dry cycle is the physical mechanism that pumps the abstract Chaperone Effect into concrete chemical reality.

## Key scales and dimensionless groups

We denote the environmental cycling frequency by  $\Omega \equiv 2\pi/\tau_{\text{cycle}}$ . The proto-system has an intrinsic (emergent) oscillation frequency  $\omega_0$  and a relaxation rate  $\gamma$ . Noise induces phase diffusion with coefficient  $D_\theta$ , so an effective phase-memory time is  $\tau_{\text{mem}} \sim 1/D_\theta$  (order of magnitude). We use the memory advantage  $\chi \equiv \tau_{\text{mem}}/\tau_{\text{env}}$ ; in the wet–dry setting a natural choice is  $\tau_{\text{env}} \sim \tau_{\text{cycle}}$ . A convenient dimensionless forcing strength is

$$\Gamma \equiv \frac{F_{\text{cycle}}}{\sqrt{D_\theta} \gamma},$$

which compares coherent periodic driving to the geometric mean of phase diffusion and relaxation rates. Entrainment requires  $\Gamma \gtrsim \mathcal{O}(1)$ .

# 2 The Physics of the Cycle

## 2.1 The Driving Force

Consider a prebiotic soup subjected to a periodic potential  $V(t) = V_0 \cos(\Omega t)$ .

- **Wet phase:** high diffusion and mixing; hydrolysis dominates (an “erasing” step).

- **Dry phase:** concentration increases and condensation reactions become favorable (a “writing” step).

This is not a passive environment. It is a **parametric driver**. The system’s parameters (concentration, pH, temperature) oscillate violently. At the microscopic level the wet–dry cycle is primarily *parametric* (it modulates effective reaction rates and mobilities); in the coarse-grained normal form we represent its net effect as an additive periodic drive on the order parameter  $z$ .

## 2.2 Dissipation-Driven Selection

England’s Dissipation-Driven Adaptation [2] shows that driven systems organize to maximize entropy production under *steady* forcing. We extend this to *periodic* forcing: the system maximizes time-averaged dissipation  $\langle \dot{S} \rangle$  by resonating with the drive. The rate of work absorption is maximized when the system’s internal response is in resonance with the drive frequency  $\Omega$ .

A "random" chemical network has no characteristic frequency; it dissipates poorly (reactively). A "looped" chemical network (autocatalytic set) has a natural frequency. If this frequency matches  $\Omega$ , the loop enters resonance. It absorbs the drive energy efficiently and uses it to repair its own entropy.

## 3 Bootstrapping the Hinge

### 3.1 The Chaperone’s Role

The Chaperone Inequality (Paper I, Theorem 1) states that trajectories with high curvature (jerk) are exponentially suppressed. In the wet-dry context, a reactive polymer that tries to fold *after* drying exhibits high curvature (rapid state change in low-mobility conditions). A reactive polymer that attempts rapid folding in the already-dry, low-mobility phase must undergo a high-curvature conformational change ( $\partial^2 r / \partial t^2$  large). The chaperone inequality assigns this trajectory an exponentially large action cost, making it non-competitive against the smooth, pre-emptive folding of a Hinge-equipped polymer. The Chaperone thus biases the population toward Hinge-possessing structures.

### 3.2 Physical Interpretation: Folding Dynamics

We interpret the complex variable  $z(t) = r(t)e^{i\theta(t)}$  as:

- $r(t)$ : Degree of polymer compaction (folding progress).
- $\theta(t)$ : Phase of the metabolic cycle (wet vs dry).

A **reactive** system has  $\phi_0 \approx 0$  (Paper III): it responds to the current environment. During drying ( $\Omega t = 0$ ),  $r$  is still small (unfolded). Folding occurs after mobility drops, leading to kinetic traps. An **anticipatory** system has  $\phi_0 < 0$  (phase lead):  $r$  increases during the *late wet phase*, before drying completes. This is the Hinge mechanism (Paper III), now applied to folding dynamics.

### 3.3 Bootstrapping the Memory Advantage

Initially,  $\chi_0 < 1$ : random polymers have no memory beyond single-cycle timescales. However, each wet–dry cycle acts as a selection step.

### Back-of-envelope cycle count (order of magnitude)

To translate the selection picture into cycles, write the crossover condition as  $\chi(N_c) \approx 1$ . If each successful cycle increases an effective persistence time by  $\Delta\tau_{\text{mem}}$  (through folding protection, encapsulation, or network closure), then

$$N_c \sim \frac{\tau_{\text{env}} - \tau_{\text{mem},0}}{\Delta\tau_{\text{mem}}}.$$

This estimate is intentionally coarse: both  $\Delta\tau_{\text{mem}}$  and  $\tau_{\text{env}}$  depend strongly on chemistry, temperature, and surfaces. For instance, with  $\tau_{\text{env}} \sim 1$  day ( $\sim 10^5$  s),  $\tau_{\text{mem},0} \sim 10^2$  s (initial persistence), and  $\Delta\tau_{\text{mem}} \sim 10^2$  s per cycle (selection increment), we get  $N_c \sim 10^3$  cycles. The key prediction is not the number itself, but that a threshold in  $N$  exists: once  $\chi$  crosses unity, lifetime and retention increase sharply due to the exponential stability scaling from Paper I. The exponential stability weight  $\mathcal{S} \propto e^{-\alpha\chi^2}$  derived in Paper I means that once  $\chi > 1$ , the protocell's lifetime increases dramatically.

## 4 The Phase Transition

We model the emergence of the loop as a phase transition in the Stuart-Landau model driven by the cycle frequency  $\Omega$ . The mapping to Stuart-Landau is coarse-grained;  $z$  represents an effective order parameter averaged over many chemical species, and the Hopf normal form captures the generic onset of oscillations under forcing.

### 4.1 The Driven Model

Let  $z$  be the state of the proto-cell.

$$\dot{z} = (\mu + i\omega_0)z - |z|^2z + F_{\text{cycle}}e^{i\Omega t} + \eta(t) \quad (4.1)$$

where  $\mu$  is the linear growth rate (Hopf bifurcation parameter),  $\omega_0$  is the natural frequency, and  $\eta(t)$  is environmental noise. For  $\mu > 0$ , the system exhibits a limit cycle even without forcing. The wet-dry cycle acts to *entrain* this cycle to the external frequency  $\Omega$ .

### 4.2 Arnold Tongues and Locking

As the forcing amplitude  $F_{\text{cycle}}$  increases, the system exhibits **Arnold tongues**: regions in the  $(\Omega, F_{\text{cycle}})$  plane where the internal frequency  $\omega_0$  locks to the drive  $\Omega$ . Inside the Arnold tongue, the winding number stabilizes at  $W = 1$  (Paper II, §3.1). The periodic forcing provides a stable phase reference and repeated selection events, effectively enlarging the basin of attraction for  $W = 1$  (locked) trajectories relative to phase-wandering ( $W$ -slipping) ones. In this sense the wet-dry cycle *pumps* the dynamics toward the topologically nontrivial sector, rather than merely permitting it.

### 4.3 The Locking Threshold

For a driven Stuart-Landau oscillator, the locking condition (1:1 resonance) occurs when  $F_{\text{cycle}} > F_c$ . For small forcing amplitude  $F_{\text{cycle}}$ , the width of the 1:1 Arnold tongue scales as  $\Delta\Omega \propto F_{\text{cycle}}$ . The locking condition requires the frequency detuning  $|\Omega - \omega_0|$  to be less than a critical value proportional to  $F_{\text{cycle}}$ . Inside the Arnold tongue, the phase locks:  $\theta(t) = \Omega t + \phi_0$ . Outside, the phase diffuses:  $\langle(\theta(t) - \Omega t)^2\rangle \sim D_\theta t$ . This connects to Paper II's  $\chi$  criterion: locking requires coherence to persist long enough to exploit the periodic reference set by the drive. In the wet-dry setting we take  $\tau_{\text{env}} \sim \tau_{\text{cycle}}$  as the dominant external timescale, so the DST condition reads  $\chi \equiv \tau_{\text{mem}}/\tau_{\text{cycle}} > 1$ . The oscillator's relaxation rate  $\gamma$  instead controls *responsiveness* (how quickly amplitude and phase can adjust), and enters naturally through the dimensionless forcing strength  $\Gamma = F_{\text{cycle}}/\sqrt{D_\theta\gamma}$ : stable entrainment requires  $\Gamma \gtrsim \Gamma_c$  with  $\Gamma_c = \mathcal{O}(1)$ .

## 5 Prebiotic Implementation

### 5.1 The Polymer Pump

During the Dry phase, amino acids condense into peptides. During the Wet phase, weak peptides hydrolyze (break apart). For example, glycine + alanine undergo condensation:



with rate constant  $k_c \sim 10^{-3} \text{ M}^{-1}\text{s}^{-1}$  (bimolecular condensation) at elevated temperature (dry phase). During rehydration, weak peptides hydrolyze with  $k_h \sim 10^{-4} \text{ s}^{-1}$ . Only peptides that fold into stable, protected structures survive the Wet phase. This is a **Darwinian selection mechanism** acting before genes exist. The “fitness function” is simply persistence against the cycle.

## 5.2 Testable Predictions

**Prediction 1: Critical Cycle Frequency** For a given chemical system (e.g., amino acid condensation), there exists an optimal cycling frequency:  $\Omega_{opt} \sim \frac{1}{\tau_{condensation}}$ .

**Prediction 2: Amplitude Threshold** Entrainment requires the forcing amplitude to overcome the phase diffusion caused by noise. This leads to a threshold condition on the **dimensionless forcing strength**

$$\Gamma \equiv \frac{F_{\text{cycle}}}{\sqrt{D_\theta} \gamma} \gtrsim \Gamma_c,$$

where  $\Gamma_c$  is an  $\mathcal{O}(1)$  constant. Below  $\Gamma_c$ , noise prevents stable phase-locking.

**Prediction 3: Memory Signature** Successful protocells should show  $\chi > 1$  measurable via  $\chi = \frac{\tau_{fold}}{\tau_{cycle}} > 1$ , where “folding time” is the autocorrelation decay time  $\tau_{fold} = \int_0^\infty dt \langle \delta r(0) \delta r(t) \rangle / \langle \delta r^2 \rangle$ , measured via fluctuation spectroscopy. In this context we operationalize  $\tau_{mem}$  as the folding/persistence autocorrelation time  $\tau_{fold}$  of the compaction variable  $r(t)$ . This can be tested in lab experiments with wet-dry cycling of RNA/peptide mixtures.

### Falsification routes

The Genesis Engine hypothesis is disfavored if:

- no entrainment band (Arnold tongue) is observed under controlled cycling across  $\Omega$  and forcing amplitude;
- no amplitude threshold consistent with  $\Gamma \gtrsim \Gamma_c$  appears (phase diffusion always dominates);
- persistence/memory proxies (e.g.  $\tau_{fold}$ ) fail to increase across cycles in the surviving subpopulation.
- no measurable increase in Arnold tongue width with increasing  $F_{\text{cycle}}$  (contradicting the predicted  $\Delta\Omega \propto F_{\text{cycle}}$  scaling).

## 5.3 From Cycle to Agency

Over thousands of cycles, the population evolves toward:

1. **Resonance:** cycling at the environmental rate.
2. **Anticipation:** folding *before* the dry phase hits (the Hinge).
3. **Closure:** forming autocatalytic loops to replenish material.

This is the birth of the Action Channel.

## 6 Conclusion: The Forced Solution

We have proposed a physically motivated route from abiotic chemistry to DST-like agency under *periodic* environmental forcing. The wet–dry cycle supplies (i) an energy source and (ii) a temporal constraint that favors phase-locked, low-curvature trajectories. Under repeated cycling, this bias

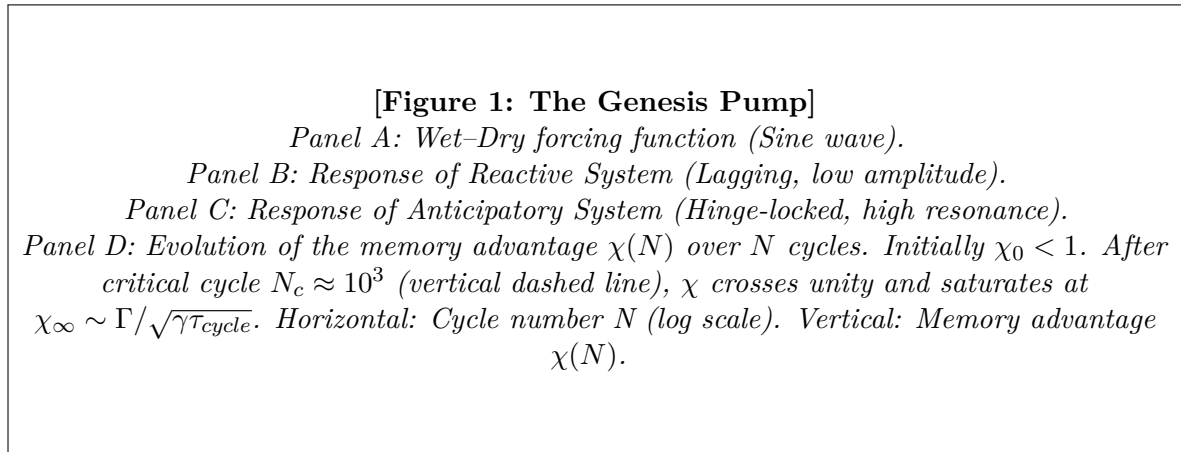


Figure 1: The Wet–Dry cycle pumps the system from disorder to agency.

stabilizes anticipatory folding/closure (the Hinge) and can bootstrap an effective memory advantage from  $\chi < 1$  to  $\chi > 1$ .

The central experimental claims are therefore: (i) a *frequency dependence* with an optimal cycling band set by intrinsic chemical timescales; (ii) an *amplitude threshold* for entrainment against noise; and (iii) a *memory signature*—an increased autocorrelation time (or reduced phase diffusion) in systems that persist across cycles.

In the final paper, *Pathology and the Blur*, we study the inverse problem: how environmental stress degrades  $\chi$  and disrupts phase locking, leading to loss of anticipatory coherence and eventual untying of the topological self.

## References

- [1] Bruce Damer and David Deamer. The hot spring hypothesis for an origin of life. *Astrobiology*, 20(4):429–452, 2020.
- [2] Jeremy L England. Statistical physics of self-replication. *The Journal of Chemical Physics*, 139(12), 2013.