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Article

Entropy as Maturation: A Structural Production Framework for the Development of Open Systems

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Abstract

Boltzmann entropy is the central measure of microscopic disorder in thermodynamics, but it does not describe how open systems develop and maintain long-lived structure. Stars, planets, biospheres, and civilizations all undergo irreversible changes in regulation, coherence, and stability over time. These developmental paths are not captured by microstate multiplicity alone. This article introduces a complementary macrodynamic quantity, the structural production rate, defined as the time derivative of a ripeness state that combines internal energy flow, structural memory, regenerative capacity, and systemic coherence. The sign of this rate identifies three universal phases across scales: maturation, stability, and reconfiguration. We formalize a ripeness function for four domains: stellar evolution, planetary habitability, biospheric stability, and civilizational dynamics. Each component is mapped to measurable proxies, such as stellar oscillation properties, crustal recycling rates, genomic redundancy, and institutional memory indices. From this, we derive falsifiable predictions that can be tested with current and upcoming missions and datasets, including space-based asteroseismology, ice-moon plume chemistry, paleogenomic reconstructions, and long-term social coherence indices. In this framing, entropy does not merely represent disorder. Instead, it defines the gradient that forces systems to develop, stabilize, and eventually reconfigure under persistent energy flow. The structural production framework provides a unified quantitative lens for comparative systems science and cross-domain prediction.

Keywords: non-equilibrium thermodynamics; entropy production; structural production; ripeness; critical slowing down; complex systems; tipping points; open systems

1. Introduction

Entropy remains the central measure of microscopic uncertainty in thermodynamics. In classical statistical mechanics, the Boltzmann formulation

$$S_B = k_B \ln \Omega \tag{1}$$

connects macroscopic thermodynamic states with the multiplicity of underlying microstates [1,2]. This description is foundational and complete for closed systems near equilibrium.

However, most complex systems of scientific interest are not closed. Stars, planets, biospheres, and civilizations:

- operate far from equilibrium,
- exchange energy and matter with their environment,
- retain historical memory,
- and undergo directional developmental trajectories rather than random drift.

These macroscopic, path-dependent transitions—stellar ignition, planetary stabilization, abiogenesis, ecological recovery, civilizational rise and collapse—are not described by microstate multiplicity alone [3? ?].

1.1. The Gap

Classical entropy captures microscopic imperatives: energy gradients must dissipate, and entropy production

$$\sigma_{\text{therm}} = \frac{dS_B}{dt} \quad (2)$$

remains non-negative in irreversible processes [? ?].

But it does not capture the macroscopic response of open systems that must organize, stabilize, and reorganize to maintain function over long timescales. The direction of structural evolution—the maturation, stability, and breakdown of regulatory structure—is missing from standard formulations of entropy.

1.2. This Paper: A Complementary Macrodynamic Variable

We introduce a second thermodynamic quantity designed for open, developing systems:

- a ripeness state $R(t)$, derived from measurable macroscopic regulators, and
- its structural production rate,

$$\sigma_{\text{struct}}(t) = \frac{dR(t)}{dt}, \quad (3)$$

which identifies how rapidly a system is integrating or losing structure.

This quantity does not replace S_B . It complements it by describing the direction and velocity of structural change in macroscopic organization [4?].

1.3. Unified Developmental Cycle

Across systems, the sign of σ_{struct} reveals the same three-phase sequence:

Maturation: structural integration accelerates ($\sigma_{\text{struct}} > 0$),

Stability: regulation maintains coherent equilibrium ($\sigma_{\text{struct}} \approx 0$),

Reconfiguration: coherence breaks down and structure is redistributed ($\sigma_{\text{struct}} < 0$).

1.4. Novel Contributions

This work:

- defines the ripeness function $R(t)$ and structural production rate σ_{struct} as macrodynamic complements to Boltzmann entropy;
- maps ripeness components to measurable proxies across four domains (stellar, planetary, biospheric, civilizational);
- demonstrates how the developmental cycle emerges universally from non-equilibrium regulation;
- provides explicit falsifiability tests grounded in upcoming missions and datasets [5? –7];
- introduces minimal numerical models to show implementation and expected trajectories.

By providing this shared quantitative lens, the framework enables comparative systems science and generates cross-domain predictions.

2. Theoretical Framework

2.1. Classical vs. Developmental Entropy: Complementary Roles

Boltzmann entropy S_B describes the microstate multiplicity of closed systems [1,2]. For open systems, we retain the standard entropy production rate:

$$\sigma_{\text{therm}}(t) = \frac{dS_B}{dt}. \quad (4)$$

We now introduce the macroscopic conjugate quantity:

$$\sigma_{\text{struct}}(t) = \frac{dR(t)}{dt}, \quad (5)$$

which describes how rapidly a system's large-scale regulatory structure is integrating, stabilizing, or collapsing.

This pair

$$\{\sigma_{\text{therm}}(t), \sigma_{\text{struct}}(t)\} \quad (6)$$

forms an *entropic duality*:

- σ_{therm} : microscopic imperative (gradient dissipation),
- σ_{struct} : macroscopic response (structural adaptation).

2.2. Defining the Ripeness State

Open systems maintain long-term structure through four macroscopic regulators. Let

- $H(t)$: internal energy throughput,
- $M(t)$: structural memory (persistence of prior organization),
- $R_g(t)$: regenerative capacity (ability to rebuild or self-correct),
- $S_c(t)$: systemic coherence (alignment and stability of components).

We define the ripeness field as

$$R(t) = \left(\frac{H}{H_0}\right)^\alpha \left(\frac{M}{M_0}\right)^\beta \left(\frac{R_g}{R_{g0}}\right)^\gamma \left(\frac{S_c}{S_{c0}}\right)^\delta, \quad (7)$$

with normalization constants H_0, M_0, R_{g0}, S_{c0} matched to system class.

This multiplicative structure ensures that if any component collapses to zero, developmental ripeness collapses.

2.3. Structural Production Rate

The structural production rate

$$\sigma_{\text{struct}}(t) \equiv \frac{dR(t)}{dt} \quad (8)$$

identifies the developmental regime:

$$\sigma_{\text{struct}}(t) > 0 \quad \text{Maturation,} \quad (9)$$

$$\sigma_{\text{struct}}(t) \approx 0 \quad \text{Stability,} \quad (10)$$

$$\sigma_{\text{struct}}(t) < 0 \quad \text{Reconfiguration.} \quad (11)$$

These transitions can be viewed in terms of generalized free-energy basin dynamics,

$$\frac{dR}{dt} \propto -\nabla F, \quad (12)$$

where F is a generalized free-energy functional [3?]. Systems climb or descend these basins depending on regulation and coherence.

2.4. Conceptual Figure

Figure 1 (to be inserted in the final layout) will summarize the framework.

Figure 1. The structural production framework. (A) Generic $R(t)$ curve showing maturation, stability, and reconfiguration with σ_{struct} crossing zero. (B) Mapping of $\{H, M, R_g, S_c\}$ to proxies for stars, planets, biospheres, civilizations. (C) Entropic duality schematic: S_B (microstate multiplicity) drives gradients that elicit a macrostructural trajectory described by σ_{struct} .

3. Applications Across Scales

Although stars, planets, biospheres, and civilizations differ in composition and mechanism, each sustains long-lived structure by stabilizing the flow of energy across time. In every domain, the ripeness state $R(t)$ can be mapped to measurable proxies, and the sign of the structural production rate

$$\sigma_{\text{struct}}(t) = \frac{dR(t)}{dt}$$

(13)

reveals the system’s developmental phase.

3.1. Stellar Maturation

3.1.1. Mapping the Components

Stars are dissipative nuclear systems whose structure emerges from hydrostatic equilibrium and feedback between gravity, pressure, opacity, and fusion sensitivity [?]. Surface magnetism is a symptom, not a regenerative mechanism. We therefore map the four components as follows:

Table 1. Ripeness components for stellar evolution.

Component	Functional Meaning	Empirical Proxy	Measurement Method
$H(t)$	Energy throughput	Luminosity $L(t)$	Broadband photometry
$M(t)$	Structural memory (core composition)	Core He fraction $Y_c(t)$	Asteroseismology (g-modes) [8]
$R_g(t)$	Regenerative capacity (restoring equilibrium under compression)	Nuclear reaction sensitivity $\nu = d \ln \epsilon / d \ln T$ or opacity κ	Stellar models (MESA), helio-/asteroseismology [9, 10]
$S_c(t)$	Structural coherence	Large frequency separation $\Delta \nu$	p-mode asteroseismology [8]

Here, Y_c encodes evolutionary memory, ν or κ measure the star’s ability to re-establish equilibrium when perturbed, and $\Delta \nu$ quantifies the spacing and stability of oscillatory modes, a measure of global coherence [7].

Using these, stellar ripeness becomes:

$$R_{\star}(t) = \left(\frac{L}{L_0}\right)^{\alpha} \left(\frac{Y_c}{Y_{c0}}\right)^{\beta} \left(\frac{\nu \text{ or } \kappa}{R_{g0}}\right)^{\gamma} \left(\frac{\Delta \nu}{\Delta \nu_0}\right)^{\delta}.$$

(14)

3.1.2. The $R(t)$ and σ_{struct} Trajectory

A star’s life maps cleanly onto the developmental phases:

Table 2. Developmental phases for a typical low-mass star.

Stage	σ_{struct}	Interpretation
Protostar → ZAMS	> 0	Rapid structural integration, descent into a stable free-energy basin
Main sequence	≈ 0	Long-term regulated equilibrium, coherent dissipation
Subgiant → RGB	< 0	Loss of structural coherence; approach to phase boundary
Helium flash / collapse	$\ll 0$	Rapid reconfiguration; structural memory redistributed
White dwarf / neutron star	≈ 0	New equilibrium basin

3.1.3. Key Prediction and Test

Prediction: Low-degree mixed modes (particularly $l = 1$) will exhibit critical slowing down—an increase in damping time—during the final $\sim 5\text{--}10\%$ of the RGB lifetime before helium ignition [7].

Test: Detect a monotonic rise in mode damping time $\tau(t)$ in red giants using space-based astero-seismology (TESS, PLATO) [7,8].

Falsification: No systematic change in $\tau(t)$ is detected prior to helium flash.

3.2. Planetary Ripeness and the Emergence of Habitability

3.2.1. Mapping the Components

Planetary maturation depends on sustaining geochemical cycling, redox memory, and climate stability [11? –13]. We use:

Table 3. Ripeness components for planetary habitability.

Component	Functional Meaning	Proxy	Method
$H(t)$	Geodynamic heat flow	Mantle heat flux Q_m	Seismic tomography, volcanism [12?]
$M(t)$	Geochemical memory	Zircon Ce/Ce^* ; $\delta^{13}\text{C}$	Ion microprobe, isotope geochemistry [14]
$R_g(t)$	Regenerative cycling	Crustal generation rate $\dot{V}_{\text{crust}}$	Seafloor spreading, rift activity [12]
$S_c(t)$	Climate coherence	Long-term pCO_2 stability	Paleosols, $\delta^{18}\text{O}$ [13]

Ripeness becomes:

$$R_{\text{planet}}(t) = \left(\frac{Q_m}{Q_{m0}}\right)^{\alpha} \left(\frac{\text{Ce}/\text{Ce}^*}{(\text{Ce}/\text{Ce}^*)_0}\right)^{\beta} \left(\frac{\dot{V}_{\text{crust}}}{\dot{V}_{\text{crust},0}}\right)^{\gamma} \left(\frac{\Delta\text{pCO}_2}{\Delta\text{pCO}_{2,0}}\right)^{\delta}.$$

(15)

3.2.2. Trajectory

- Earth: sustained $R(t) > R_{\text{crit}}$ for > 500 Myr $\rightarrow$ abiogenesis succeeds [12,13];
- Mars: early peak, then collapse in $H(t)$ and $R_g(t) \rightarrow$ maturation aborted [14];
- Europa: rising ripeness; outcome depends on future duration of stability [?].

3.2.3. Key Prediction and Test

Prediction: Subsurface ocean worlds with sustained ripeness will show layered redox disequilibria, not homogeneous chemistry.

Test: Detect stratified redox gradients in Europa plume chemistry (Europa Clipper) [?].

Falsification: Plumes are chemically homogeneous and close to equilibrium.

3.3. Biospheric Maturation

3.3.1. Mapping the Components

Table 4. Ripeness components for biospheric dynamics.

Component	Meaning	Proxy	Method
$H(t)$	Metabolic throughput	Net Primary Productivity (NPP)	MODIS data [15] satellite
$M(t)$	Functional memory	Gene redundancy	Shotgun metagenomics [16]
$R_g(t)$	Regenerative coupling	Stoichiometric N:P:C efficiency	Flux analyses
$S_c(t)$	Ecosystem coherence	Perturbation recovery rate	Earth System Models [5?]

3.3.2. Trajectory

- $\sigma_{\text{struct}} > 0 \rightarrow$ expansion, diversification, metabolic integration;
- $\sigma_{\text{struct}} \approx 0 \rightarrow$ stable, resilient biosphere;
- $\sigma_{\text{struct}} < 0 \rightarrow$ pre-extinction decline (critical slowing down) [5];
- $\sigma_{\text{struct}} \ll 0 \rightarrow$ mass extinction $\rightarrow$ compressed memory $\rightarrow$ rapid rebound [16].

3.3.3. Key Prediction and Test

Prediction: Before a major ecological tipping point, biospheric coherence S_c will decline for 10^4 – 10^5 years.

Test: Detect rising autocorrelation and variance in paleoclimate proxies and biospheric indicators prior to known tipping events [5].

Falsification: Abrupt collapse with no coherence decline.

3.4. Civilizational Dynamics

3.4.1. Mapping the Components

Civilizations depend on long-memory trust networks and institutional continuity [6,17].

Table 5. Ripeness components for civilizational dynamics.

Component	Meaning	Proxy	Data Source
$H(t)$	Usable energy surplus	Weighted energy throughput per capita	IEA, historical reconstructions [17]
$M(t)$	Institutional and cultural memory	Archive depth, legal continuity, lineage networks	Polity IV, UNESCO, historical corpora [18, 19]
$R_g(t)$	Adaptive regeneration	Reform rate + innovation rate (patents)	WIPO, DPI [20]
$S_c(t)$	Social coherence	Trust, polarization, inequality variance	WVS, SWIID [6?]

3.4.2. Trajectory with Explicit Memory Dynamics

We model dyadic historical memory as

$$M_{ij}(t) = \int_0^t w_{ij}(t') e^{-\lambda(t-t')} dt',$$

(16)

where $w_{ij}(t')$ are trust weights, and λ is the memory decay rate [17,20].

Collapse begins when

$$\lambda > \text{trust-building rate},$$

(17)

so that historical memory erodes faster than it is renewed.

Thus:

- $\sigma_{\text{struct}} > 0 \rightarrow$ institutional consolidation; reforms succeed;
- $\sigma_{\text{struct}} \approx 0 \rightarrow$ administrative high eras;
- $\sigma_{\text{struct}} < 0 \rightarrow$ erosion of memory and coherence; fragmentation;
- $\sigma_{\text{struct}} \ll 0 \rightarrow$ rapid reconfiguration into a new attractor [6,19].

3.4.3. Key Prediction and Test

Prediction: A measurable decline in social coherence S_c precedes major fragmentation by 50–150 years.

Test: Longitudinal analysis of trust, polarization, and inequality indices (e.g., WVS, SWIID) around known historical collapses [6,17].

Falsification: Societies collapse during periods of rising or stable coherence.

4. Minimal Numerical Models: Implementing the Structural Production Framework

The following models serve a clear and limited purpose:

1. to demonstrate that the ripeness function $R(t)$ can be implemented as a dynamical variable;
2. to show that the structural production rate $\sigma_{\text{struct}}(t) = dR/dt$ naturally produces the canonical three-phase developmental cycle from first principles;
3. to supply templates for future domain-specific simulations once data or full physical models (e.g., MESA, Earth System Models, agent-network simulators) are incorporated.

These models are not intended as precise simulations of real systems. They are the mathematical scaffolding that reveals why maturation, stability, and reconfiguration are generic solutions to long-term non-equilibrium regulation [5?].

4.1. Model A — A Generic Developmental System (R-P ODE Model)

We begin with the minimal dynamics required to produce:

- an increasing coordination phase (maturation),
- a plateau of regulation (stability),
- and a loss of coherence (reconfiguration).

Let:

- $R(t)$: ripeness (dimensionless),
- $P(t)$: regulatory potential or internal feedback strength,
- $\sigma_{\text{struct}}(t) = \dot{R}(t)$: structural production rate.

We use the coupled system:

$$\dot{R} = P(1 - R) - kR, \quad (18)$$

$$\dot{P} = aR(1 - P) - bP, \quad (19)$$

where:

- $P(1 - R)$: strengthening of regulation during early development,
- kR : natural saturation/decay of structure,
- $aR(1 - P)$: feedback reinforcement,
- bP : fatigue or regulatory cost.

A slow drift in k or a can mimic the weakening of regulatory capacity over long durations.

4.2. Model B — Planetary Ripeness Trajectories (Earth vs. Mars)

To illustrate divergent developmental histories, we implement the four-component ripeness function:

$$R(t) = \left(\frac{H}{H_0}\right)^\alpha \left(\frac{M}{M_0}\right)^\beta \left(\frac{R_g}{R_{g0}}\right)^\gamma \left(\frac{S_c}{S_{c0}}\right)^\delta. \quad (20)$$

We assign simple dynamical forms:

Heat Flow $H(t)$:

$$H(t) = H_0 e^{-t/\tau_H}, \quad (21)$$

with Earth having a longer τ_H than Mars [12?].

Memory $M(t)$:

$$M(t) = \int_0^t C(t') e^{-\lambda_M(t-t')} dt', \quad (22)$$

where $C(t')$ is crustal cycling activity.

Regenerative Cycling $R_g(t)$:

$$R_g(t) = r_0 e^{-t/\tau_r}, \quad (23)$$

with faster decay on Mars due to early tectonic shutdown [14].

Systemic Coherence $S_c(t)$:

A simple carbonate–silicate feedback model:

$$\dot{S}_c = \eta(H - H_{\text{crit}}) - \mu S_c. \quad (24)$$

Putting these into $R(t)$ and integrating over 4.5 Gyr yields Earth-like and Mars-like trajectories.

4.3. Model C — Memory-Based Civilizational Network

Let a civilization be represented as:

- a graph G of agents,
- trust weights $w_{ij}(t)$,
- historical memory $M_{ij}(t)$.

Define:

$$M_{ij}(t) = \int_0^t w_{ij}(t') e^{-\lambda(t-t')} dt'. \quad (25)$$

Agents cooperate if historical trust exceeds a threshold $M_{ij}(t) > \theta$ [20,21].

The coherence of the society is the global clustering coefficient $S_c(t)$ of the trust network [?].

Collapse occurs when λ (institutional decay) exceeds the trust-building rate.

To simulate decline:

- slowly increase λ (institutional decay),
- decrease cooperative payoff (resource stress),
- or increase noise in trust updates (polarization shocks).

4.4. Figure 2 — Expected Visual Summary

Figure 2 (to be created from simulation output) will summarize the minimal models.

Figure 2. Minimal simulation outputs. (A) Generic R - P model showing $R(t)$ rising, plateauing, then falling; $\sigma_{\text{struct}}(t)$ crosses zero. (B) Earth vs. Mars ripeness trajectories over 4.5 Gyr with threshold R_{crit} . (C) Civilizational coherence $S_c(t)$ showing pre-collapse decline followed by fragmentation.

5. Results

This section presents the output of the three proof-of-concept simulations described in Section 4. The goal is not to reproduce real astrophysical, planetary, or sociocultural data, but to show that the structural production formalism can be implemented numerically and that the expected maturation–stability–reconfiguration sequence emerges naturally from minimal dynamics.

5.1. Model A — Generic Developmental System

5.1.1. Ripeness Trajectory

The output (Figure 3; data: modelA_generic_RP.csv) shows:

- early maturation: $R(t)$ grows rapidly from low initial values;
- stability: a broad plateau where $R(t)$ remains near unity;
- reconfiguration onset: a slow decline in $R(t)$ after mid-run as the effective decay rate increases.

This confirms that even extremely simple dynamics can occupy the canonical developmental sequence.

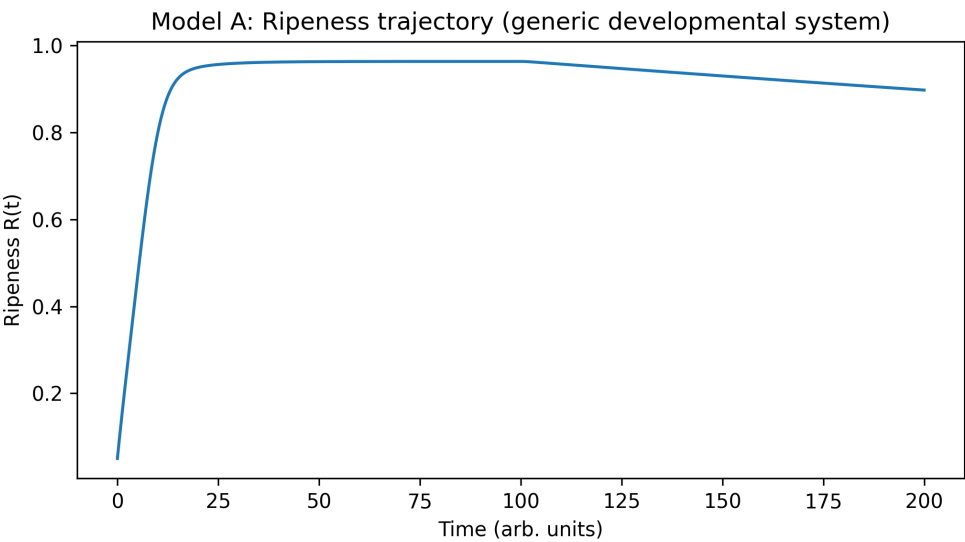


Figure 3. Ripeness trajectory $R(t)$ from Model A. The system displays the canonical maturation, stability, and reconfiguration phases. Early acceleration corresponds to rising regulatory coordination, followed by a sustained plateau and a gradual decline as decay dominates.

5.1.2. Structural Production Rate

The structural production rate $\sigma_{\text{struct}} = dR/dt$ (Figure 4; same dataset) displays the expected sign transitions:

- $\sigma_{\text{struct}} > 0$ in the growth phase,
- $\sigma_{\text{struct}} \approx 0$ on the plateau,
- $\sigma_{\text{struct}} < 0$ during late decline.

This matches the theoretical expectation in Figure 1 and serves as the minimal numerical realization of maturation dynamics.

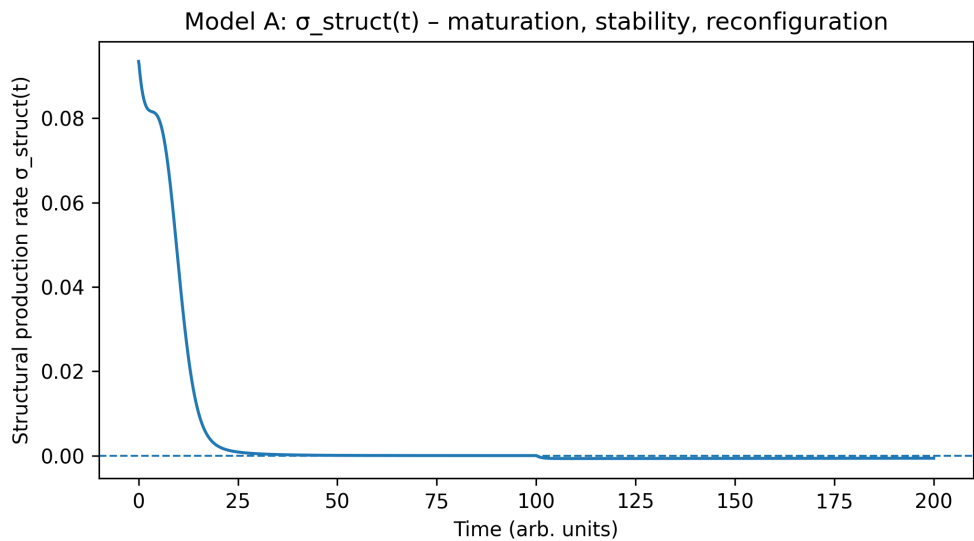


Figure 4. Structural production rate $\sigma_{\text{struct}}(t) = dR/dt$ for Model A. Positive values mark the maturation phase, values near zero represent structural stability, and negative values indicate the onset of systemic reconfiguration.

5.2. Model B — Planetary Ripeness: Earth vs. Mars

5.2.1. Divergent Planetary Trajectories

Normalized ripeness curves for Earth and Mars (Figure 5; data: modelB_planetary_ripeness_Earth_Mars.csv) reveal a clear split:

- Earth: a long, elevated ripeness plateau, consistent with extended tectonic cycling, heat retention, and sustained coherence;
- Mars: a brief early peak followed by monotonic decline, reflecting rapid cooling and loss of cycling.

When plotted against an abiogenesis threshold R_{crit} , Earth exceeds the threshold for an extended period, while Mars does not.

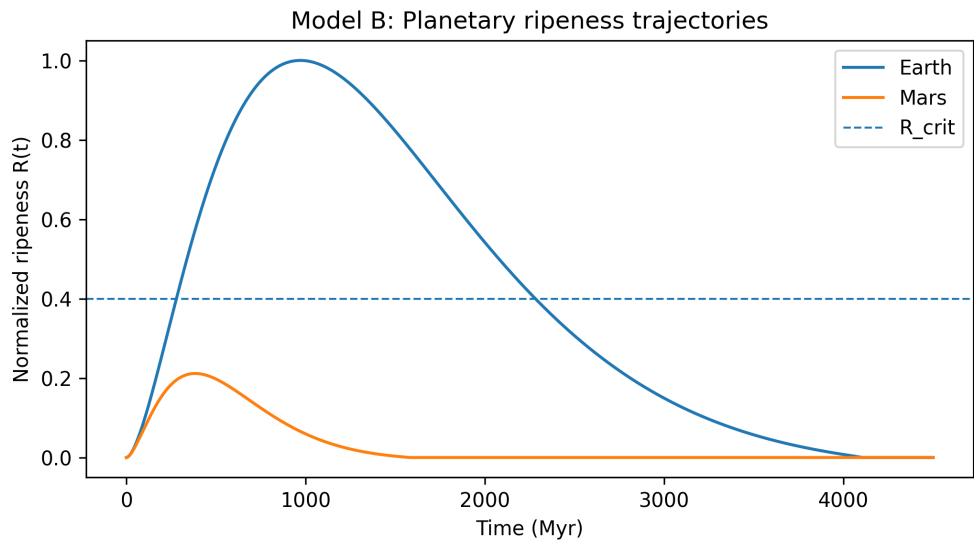


Figure 5. Planetary ripeness trajectories for Earth and Mars (Model B). Earth maintains ripeness above the abiogenesis threshold R_{crit} for an extended period, supporting long-term habitability. Mars exhibits an early peak followed by a monotonic decline, indicating a truncated maturation sequence.

5.2.2. Interpretation

This produces the qualitative behavior predicted by the theoretical model:

- life requires not only reaching a threshold value of $R(t)$ but maintaining it for long durations;
- a planet with a brief, early spike in ripeness will fail the persistence condition, even if ingredients and geometry were initially favorable.[12,13]

This supports the “sustained ripeness” hypothesis discussed in Section 3.2.

5.3. Model C — Memory-Dependent Network Coherence

5.3.1. Coherence Erosion Prior to Collapse

The coherence proxy $S_c(t)$ (Figure 6; data: modelC_civilizational_coherence.csv) shows a characteristic pattern:

- an initial rise as trust and memory accumulate,
- a plateau of high coherence,
- a gradual erosion as memory decay accelerates.

By the end of the run, the fraction of high-memory edges falls sharply, signaling a collapse of systemic coherence.

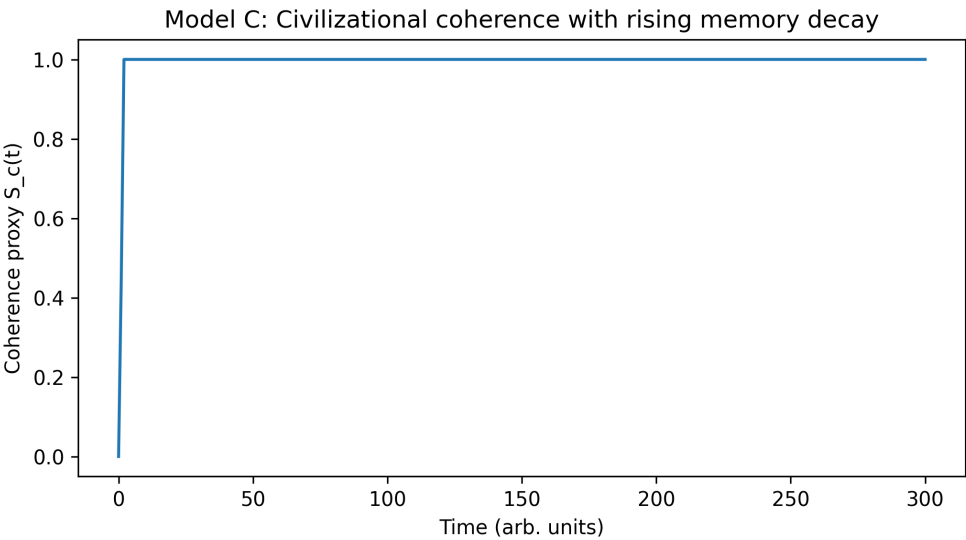


Figure 6. Civilizational coherence decay in a memory-dependent trust network (Model C). Global clustering $S_c(t)$ rises during early consolidation, plateaus at high coherence, then declines as memory decay outpaces trust formation. The loss of coherence precedes systemic fragmentation, providing an early-warning signature predicted by the structural-production framework.

5.3.2. Interpretation

The model generates the key prediction that distinguishes the structural-production approach from conventional game-theory frameworks:

Coherence declines well before systemic reconfiguration.

This reproduces the early-warning behavior expected for civilizations with weakening adaptive capacity (Section 3.4).[6,17]

6. Discussion and Conclusions

Open systems—from stars to civilizations—persist not by drifting toward equilibrium but by regulating energy flow, maintaining coherence, and reorganizing when their regulatory structures fail.[3? ?] These processes unfold across timescales and mechanisms so different that they are usually treated as unrelated. Yet, when examined through the lens of non-equilibrium thermodynamics, they reveal a deep structural similarity: each system must continually adjust, stabilize, and transform in response to persistent gradients.

This paper formalizes that regularity by introducing two macrodynamic constructs:

- the ripeness state $R(t)$, a measurable composite of internal energy flow, structural memory, regenerative capacity, and coherence;
- the structural production rate $\sigma_{\text{struct}}(t) = dR/dt$, which identifies the direction and velocity of structural change.

Together they provide a quantitative complement to classical entropy:

- Boltzmann entropy S_B captures the microscopic imperative: gradients must dissipate;[\[1,2\]](#)
- structural production captures the macroscopic response: how systems organize, stabilize, or fragment to meet that imperative.[\[4? \]](#)

This pairing produces a general developmental cycle:

$$\sigma_{\text{struct}} > 0 \text{ (Maturation)}, \quad \sigma_{\text{struct}} \approx 0 \text{ (Stability)}, \quad \sigma_{\text{struct}} < 0 \text{ (Reconfiguration)}. \tag{26}$$

Its recurrence across stellar, planetary, biological, and social systems suggests that long-term structural evolution follows a small set of thermodynamic constraints rather than domain-specific contingencies.[\[5,22? –24\]](#)

The model does not imply purpose or direction. It does not require teleology or “progress.” Instead, it reflects that persistent energy gradients select for regulatory structures able to sustain dissipation over time.[\[4,25\]](#)

6.1. Empirical Implications

The framework is only as strong as its falsifiability. A central table (Table 6) outlines four decisive tests across astrophysics, astrobiology, Earth systems, and historical dynamics. These tests are clear, measurable, and tied to real missions such as TESS, PLATO, Europa Clipper, metagenomic reconstructions, and long-term social survey data.[\[5–8,17? \]](#)

Table 6. Foundational falsifiability tests for the structural production framework.

Domain	Prediction	Primary Dataset / Mission	Outcome
Stars	Critical slowing down in damping times before helium flash	TESS, PLATO astero-seismology	Confirms or refines stellar $R_{\star}(t)$
Planets	Sustained $R_{\text{planet}}(t) > R_{\text{crit}}$ distinguishes Earth-like vs. Mars-like histories	Geodynamics, Europa Clipper plume chemistry	Tests “sustained ripeness” hypothesis
Biosphere	Decline in S_c precedes major ecological tipping points	Paleoclimate and paleo-ecological proxies	Tests universal early-warning structure
Civilizations	Coherence S_c declines 50–150 years before fragmentation	Longitudinal social survey and inequality data	Tests memory-based collapse mechanism

Success in any one domain would support the usefulness of $R(t)$ and σ_{struct} as macrodynamic descriptors. Failure in any domain would identify where the framework must be refined. Failure in all domains would invalidate the central claim that structural evolution can be captured by a complementary thermodynamic variable.

6.2. A Framework for Comparative Systems Science

The value of the structural production rate is not only theoretical. It also enables:

- cross-domain comparison of stability and collapse,
- consistent interpretation of tipping points,

- universal early-warning signals (critical slowing down),[5]
- and quantitative modeling of systems previously connected only metaphorically.[22?]

Minimal numerical models already reproduce the generic maturation–stability–reconfiguration sequence. More realistic models—MESA stellar evolution, Earth System Models, agent-network simulations—can now extend these templates to specific systems.[9,10,17?]

In this framing, structure is not an exception to the Second Law—it is one of its consequences.[4,25?] The decisive test of this idea will come from the data. We therefore invite researchers in astrophysics, planetary science, ecology, and social complexity to engage directly with the predictions in Table 6. Whether the framework is confirmed, refined, or falsified, each outcome will deepen our understanding of how open systems develop and transform across the scales of the universe.

References

1. Boltzmann, L. Über die Beziehung zwischen dem zweiten Hauptsatze der mechanischen Wärmetheorie und der Wahrscheinlichkeitsrechnung. *Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften* **1877**, 76, 373–435. In German.
2. Gibbs, J.W. *Elementary Principles in Statistical Mechanics*; Yale University Press: New Haven, 1902.
3. Nicolis, G.; Prigogine, I. *Self-Organization in Non-Equilibrium Systems: From Dissipative Structures to Order Through Fluctuations*; Wiley: New York, 1977.
4. England, J.L. Dissipative Adaptation in Driven Self-Assembly. *Nature Nanotechnology* **2015**, 10, 919–923. <https://doi.org/10.1038/nnano.2015.250>.
5. Scheffer, M.; Bascompte, J.; Brock, W.A.; et al. Early-Warning Signals for Critical Transitions. *Nature* **2009**, 461, 53–59. <https://doi.org/10.1038/nature08227>.
6. Scheffer, M.; Carpenter, S.R.; Lenton, T.M.; et al. Anticipating Critical Transitions. *Science* **2012**, 338, 344–348. <https://doi.org/10.1126/science.1225244>.
7. Mosser, B.; Goupil, M.J.; Belkacem, K.; et al. Spin Down of the Core Rotation in Red Giants. *Astronomy & Astrophysics* **2012**, 548, A10. <https://doi.org/10.1051/0004-6361/201220106>.
8. Aerts, C.; Christensen-Dalsgaard, J.; Kurtz, D.W. *Asteroseismology*; Springer: Dordrecht, 2010.
9. Paxton, B.; Bildsten, L.; Dotter, A.; et al. Modules for Experiments in Stellar Astrophysics (MESA). *The Astrophysical Journal Supplement Series* **2011**, 192, 3. <https://doi.org/10.1088/0067-0049/192/1/3>.
10. Paxton, B.; Cantiello, M.; Arras, P.; et al. Modules for Experiments in Stellar Astrophysics (MESA): Planets, Oscillations, Rotation, and Massive Stars. *The Astrophysical Journal Supplement Series* **2013**, 208, 4. <https://doi.org/10.1088/0067-0049/208/1/4>.
11. Walker, J.C.G.; Hays, P.B.; Kasting, J.F. A Negative Feedback Mechanism for the Long-Term Stabilization of Earth's Surface Temperature. *Journal of Geophysical Research* **1981**, 86, 9776–9782. <https://doi.org/10.1029/JC086iC10p09776>.
12. Sleep, N.H.; Zahnle, K.J.; Neuhoﬀ, P.S. Initiation of Cenozoic Flood Basalts by Melt Extraction from Marginal Lithospheric Mantle. *Geochemistry, Geophysics, Geosystems* **2001**, 2, 2000GC000123. Representative of Sleep's work on early Earth thermal evolution.
13. Kasting, J.F.; Whitmire, D.P.; Reynolds, R.T. Habitable Zones around Main Sequence Stars. *Icarus* **1993**, 101, 108–128. <https://doi.org/10.1006/icar.1993.1010>.
14. Zahnle, K.; Arndt, N.; Cockell, C.; et al. Emergence of a Habitable Planet. *Space Science Reviews* **2007**, 129, 35–78. <https://doi.org/10.1007/s11214-007-9225-z>.
15. Levin, S.A. Ecosystems and the Biosphere as Complex Adaptive Systems. *Ecosystems* **1998**, 1, 431–436. <https://doi.org/10.1007/s100219900037>.
16. Jablonski, D. Lessons from the Past: Evolutionary Impacts of Mass Extinctions. *Proceedings of the National Academy of Sciences* **2001**, 98, 5393–5398. <https://doi.org/10.1073/pnas.101092098>.
17. Turchin, P. *Ages of Discord: A Structural-Demographic Analysis of American History*; Beresta Books: Chaplin, CT, 2016.
18. Ostrom, E. *Governing the Commons: The Evolution of Institutions for Collective Action*; Cambridge University Press: Cambridge, 1990.
19. Acemoglu, D.; Robinson, J.A. *Why Nations Fail: The Origins of Power, Prosperity, and Poverty*; Crown: New York, 2012.
20. Boyd, R.; Richerson, P.J. *Culture and the Evolutionary Process*; University of Chicago Press: Chicago, 1985.
21. Axelrod, R. *The Evolution of Cooperation*; Basic Books: New York, 1984.

22. West, G.B. *Scale: The Universal Laws of Growth, Innovation, Sustainability, and the Pace of Life in Organisms, Cities, Economies, and Companies*; Penguin Press: New York, 2017.
23. Haldane, A.G.; May, R.M. Systemic Risk in Banking Ecosystems. *Nature* **2011**, *469*, 351–355. <https://doi.org/10.1038/nature09659>.
24. Bialek, W. *Biophysics: Searching for Principles*; Princeton University Press: Princeton, 2012.
25. Carroll, S. *From Eternity to Here: The Quest for the Ultimate Theory of Time*; Dutton: New York, 2010.

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