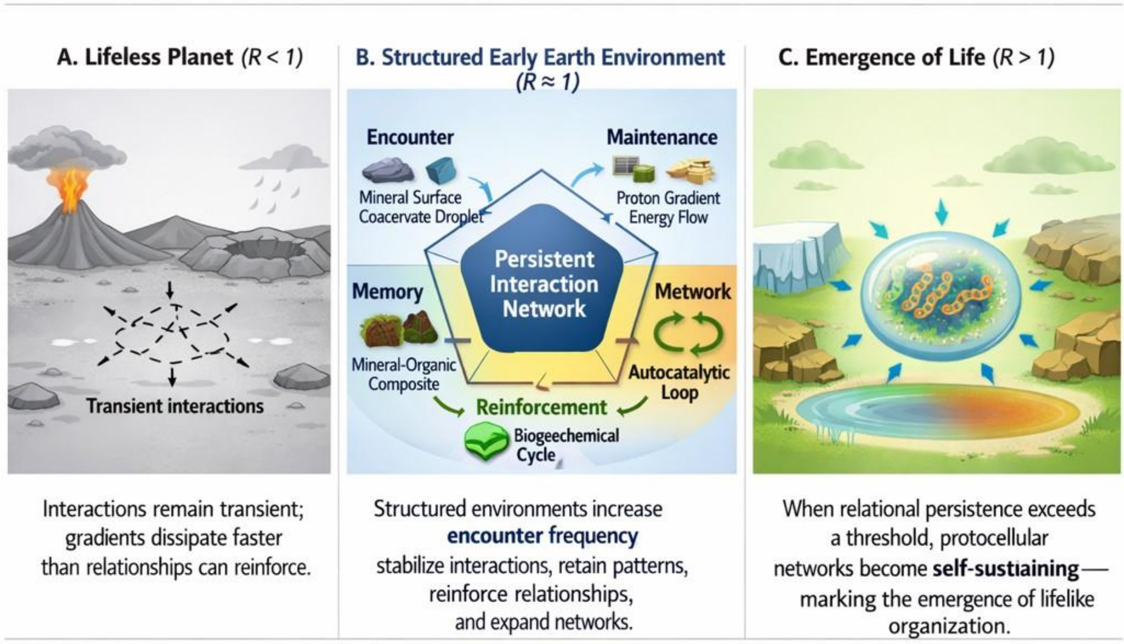
Why Are Lifeless Planets Desolate?
Life as the Emergent Knot of Environmental Activity_2



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Abstract

Life emerges when interactions persist long enough to reinforce and reorganize themselves. Here, I propose relational persistence (R) as a conceptual measure of an environment's ability to sustain interactions beyond dissipation, summarizing five factors—encounter, maintenance, memory, reinforcement, and network expansion—that together determine whether chemical and physical relationships can accumulate into a self-maintaining organization. When these factors collectively exceed a threshold (R > 1), interactions become persistent, enabling the transition from transient chemistry to lifelike structure. This essay proposes a conceptual framework for understanding the emergence of life, rather than a quantitative model, and from this perspective, lifeless planets remain barren not because they lack chemical activity, but because their environments fail to sustain persistent relationships. This relational view suggests experimentally and observationally testable avenues in prebiotic chemistry and astrobiology, including enhanced network lifetimes, pattern retention, and emergent organization in structured, cyclic, and gradient-rich environments. Life may thus be understood as the first system in Earth's history in which R exceeded 1—the first environment capable of sustaining and extending its own relationships.

Keywords: Relational persistence; Origin of life; Prebiotic chemistry; Astrobiology; Emergent organization

Introduction

Lifeless planets show that chemistry alone does not organize itself; the origin of life is the origin of persistent relationships, not the origin of molecules. Mars, Venus, and the Moon all possess energy sources, active geology, and abundant chemical reactions, yet none of these processes accumulate into lasting structure. Winds reshape surfaces, impacts redistribute material, and gradients arise only to dissipate. These planets remain barren because their environments fail to generate the stable, reinforcing interactions required for sustained complexity.

This reframes the central question. Instead of asking why life emerged on Earth, we must ask why it failed to emerge elsewhere. What distinguishes an environment capable of sustaining relationships from one that continually erodes them?

This question extends far beyond early Earth. Modern complex systems—from artificial intelligence to climate networks and social infrastructures—demonstrate that the persistence of relationships, rather than the properties of individual components, determines whether a system becomes stable, adaptive, or collapses. AI models exhibit emergent capabilities only when internal interactions reinforce one another; climate systems destabilize when ecological relationships weaken; social networks fragment when relational ties decay. These examples reveal a general principle: systems thrive when relationships persist and fail when they do not.

Life is often described as a collection of molecules, reactions, and informational polymers. Yet none of these elements, taken alone, explains why living systems emerge at all. What remains insufficiently addressed is the origin of relationships—the persistent, structured interactions that allow matter to maintain itself, to cohere, and eventually to evolve. I propose that the origin of life is fundamentally the origin of such relationships, arising from the physical and ecological structure of early environments.

Early Earth was not a homogeneous reaction vessel. It was a landscape of mineral surfaces, porous matrices, multiphase interfaces, and persistent gradients (Hazen & Sverjensky 2010; Kelley et al. 2005; Deamer 2017). These structured environments created microhabitats in which molecules could repeatedly encounter one another, remain in proximity, and form interactions that lasted longer than the fluctuations that threatened to dissolve them. Life begins not with isolated molecules, but with environments capable of sustaining persistent interactions.

To describe this idea concisely, I introduce a conceptual parameter: relational persistence R. R is not a quantitative metric but a summary of five relational dimensions—encounter, maintenance, memory, reinforcement, and network expansion. When these factors collectively allow interactions to sustain themselves, R exceeds a threshold at which relationships become self-maintaining:

R > 1

This threshold marks a conceptual transition from transient chemistry to lifelike organization—and explains why lifeless planets remain below it.

Encounter: Structured environments that promote repeated interactions

Mineral surfaces concentrate reactants through adsorption–desorption cycles (Hazen & Sverjensky, 2010). Phase-separated droplets and coacervates create microreactors with elevated local concentrations (Deamer & Dworkin, 2005). Microporous structures in hydrothermal chimneys restrict diffusion, prolonging residence times and increasing encounter frequency (Kelley et al. 2005). These settings transform random collisions into persistent opportunities for interaction.

In structured environments, prebiotic networks may exhibit longer lifetimes and higher connectivity than in homogeneous solutions.

Maintenance: Energetic and structural stabilization of interactions

Persistent energy gradients—particularly proton gradients across mineral barriers in alkaline hydrothermal systems—could drive and maintain reaction cycles (Russell & Martin 2004; Lane & Martin 2012). Autocatalytic sets reinforce their own components, enabling partial self-maintenance (Kauffman 1993; Hordijk & Steel 2017). Phase-separated compartments buffer reactions from external perturbations, protecting fragile intermediates (Damer & Deamer 2020).

In environments with stable energy gradients, prebiotic networks may exhibit forms of partial self-maintenance that are experimentally detectable.

Memory: Recording relational patterns before genetics

Before nucleic acids, relational patterns must have been retained in physical structures. Mineral–organic composites can preserve reaction sequences across cycles (Hazen & Sverjensky, 2010). Polymer-rich condensates retain spatial organization and chemical gradients, enabling recurrence of reaction patterns (Deamer & Dworkin, 2005). These systems preserve relational configurations—patterns of interaction that can recur and accumulate.

Prebiotic systems may retain measurable patterns of interaction even in the absence of nucleic acids.

Reinforcement: Evolution as the strengthening of relationships

Once interactions persist long enough to influence one another, reinforcement becomes possible. Repeated interactions stabilize cooperation. Horizontal transfer spreads beneficial relational patterns. Symbiosis integrates previously separate networks, as seen in the origins of mitochondria and chloroplasts (Lane & Martin 2012). Evolution becomes the progressive reinforcement of relationships.

Early evolutionary dynamics may reflect cooperative stabilization of interactions rather than purely competitive exclusion.

Network expansion: Ecosystems as relational architectures

As relationships accumulate and reinforce one another, they expand into larger networks. Biogeochemical cycles distribute relational effects across environments. Food webs create hierarchical relational structures. Ecosystem engineering modifies environments in ways that stabilize and extend relational networks (Russell & Martin 2004). Life becomes an ecological phenomenon long before it becomes a genetic one.

Life-bearing systems may be expected to exhibit network-level organization rather than isolated replicators. Together, these observations suggest avenues for experimentally and observationally probing relational persistence in prebiotic and planetary systems.

A Relational Threshold

These five dimensions can be summarized by a single conceptual condition:

$R > 1$

R represents the overall persistence of interactions—their ability to continue, reinforce themselves, and resist dissipation. When R exceeds 1, relationships become self-sustaining. This threshold captures the essence of relational emergence.

Conclusion

Lifeless planets are desolate not because they lack the building blocks of life, but because their environments fail to generate relationships that persist. Their chemical and physical processes do not reinforce one another; their structures do not stabilize subsequent structures; their interactions do not accumulate into networks. In relational terms, their environments remain in a regime where $R < 1$. While R is introduced here as a conceptual construct, future work may explore quantitative or operational proxies for its components.

Early Earth crossed this threshold. Its structured environments allowed interactions to persist, reinforce themselves, and expand into networks capable of maintaining their own organization. When $R > 1$, relationships became self-sustaining, marking the emergence of lifelike organization.

This relational perspective also illuminates contemporary challenges. Modern complex systems—AI architectures, climate networks, and social infrastructures—succeed or fail for the same reason early chemical systems did: the persistence of relationships. AI models exhibit emergent capabilities only when internal interactions reinforce one another rather than dissipate. Climate systems destabilize when ecological relationships weaken faster than they can be repaired. Social networks fragment when relational ties decay and cannot be renewed. These examples do not serve as metaphors but as demonstrations of a general principle: systems remain functional only when R exceeds 1—when interactions persist long enough to reinforce and reorganize themselves.

Life, therefore, is not defined by a molecule, a replicator, or a metabolism. Life may be understood as the first system in Earth's history in which R exceeded 1—the first environment that learned to hold its own structure together. This shift in perspective explains not only why Earth is alive but also why lifeless planets remain barren: without relational closure, no environment—planetary, computational, ecological, or social—can become more than a sequence of transient processes.

Declarations

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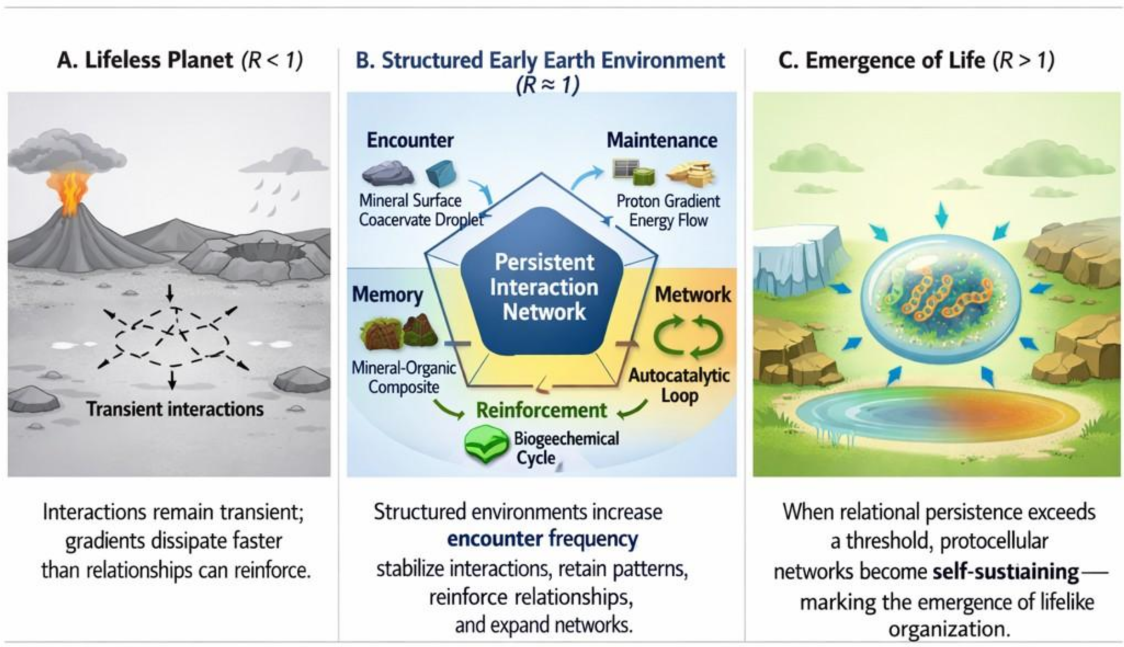

Figure 1. Relational Persistence (R) and the Emergence of Persistent Organization

(A) Lifeless planets remain in a regime where interactions dissipate rapidly ($R < 1$).
(B) Structured environments on early Earth increased encounter frequency, stabilized interactions, retained patterns, reinforced relationships, and expanded networks ($R \approx 1$).
(C) When relational persistence exceeded a threshold ($R > 1$), protocellular networks became self-sustaining, marking the emergence of lifelike organization. Figure created by the author using Microsoft Copilot (AI-assisted illustration).