

Turtles, or Crystals

A Speculative Synthesis on Substrate-Independent Life and the Topological Defect as Memory, Morphogen, and Transducer

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This synthesis deliberately brackets any numerological or cosmological framing and rests only on established artificial-life, origin-of-life, condensed-matter, and evolutionary literature.

Abstract

Several traditions in artificial life and origin-of-life research converge on one claim: that life is an organization rather than a material. We take that claim seriously and ask whether a single class of crystalline lattice defect could supply, in one physical feature, three functions a minimal living system needs at once — heritable memory, the shaping of form, and the transduction of mechanical state into signal — and whether such a substrate would behave as a self-healing, fault-tolerant information network. We assemble established results from artificial life, mineral-origin-of-life theory, information-theoretic accounts of life, condensed-matter defect physics, and quasispecies theory, and identify a candidate “triple-duty part”: the topologically protected lattice defect, which stores anneal-resistant state, concentrates the curvature that sculpts growth, and produces local electric polarization through flexoelectricity. We argue that topological protection is the specific physical fix for the low-fidelity wall that ended the mineral-heredity program, and that a crystalline replicator should therefore possess an Eigen error threshold set by its defect-copying fidelity. The individual ingredients are all established; the contribution is their synthesis and two falsifiable bridges. We are explicit that this is speculation, mark every seam between grounded physics and conjecture, and close with concrete testable predictions on existing platforms. The aim is to provoke a grounded, cross-disciplinary conversation and to be freely reusable by anyone who can take it further.

1. Introduction: life as it could be

The old image of the world resting on a turtle, and that turtle on another, turtles all the way down, is at heart a question about foundations — what ultimately holds things up. This paper asks it of life: whether the support underneath must be carbon chemistry, or whether it could continue down through crystal instead. Whether life must be made of what Earth’s life is made of is an old question. Christopher Langton founded artificial life as the study of “life as it could be” rather than “life as we know it,” aiming at a general theoretical biology valid whatever life’s material basis [1]; von Neumann, building self-reproducing automata, treated heredity as a logical organization abstractable from any

medium [2]. If that abstraction is real, a useful exercise is to take a non-biological substrate and ask whether the minimal functional ingredients of a living system — a way to sense, to store state, to make a binary distinction, to advance through ordered steps — already live in its ordinary physics. This paper follows that question across several literatures to a single candidate part, and then asks what would falsify the picture.

2. Substrate independence is an old and founded idea

The claim that life is organization, not matter, is the founding premise of an established field, not a novelty of this paper [1,2]. We inherit it as a starting point. What we attempt is narrower: to locate, in one specific non-carbon substrate, a concrete feature that could carry several biological functions at once, and to say how it could be tested.

3. The mineral precedent and the fidelity wall

Crystalline proto-life has serious precedent. A. G. Cairns-Smith proposed that the first hereditary systems were inorganic — lattice defects in growing minerals that replicate and undergo selection, with organic molecules later performing a “genetic takeover” [3]. The program hit a hard wall: when crystal-defect information replication was actually examined, fidelity was very low [4], because a crystal’s natural tendency is to anneal defects away, erasing the very variation selection needs. The same line of work shows the wall is not absolute — Schulman, Yurke, and Winfree achieved robust replication of combinatorial information by crystal growth and scission using DNA tiles, far above raw defect-copying fidelity [4]. The lesson we carry forward, and sharpen below, is that low fidelity is a property of the chemistry one chooses, not a law of crystals.

4. Information, not matter, as the conserved quantity

If the medium can vary, what is conserved is the organization of information. Walker and Davies frame the origin of life as a transition in causal structure, where information gains context-dependent control over its matter [5]; assembly theory makes a related idea quantitative, defining objects by their formation histories and measuring the selection required to produce them [6] (a framework actively contested, which we treat as a candidate measure, not a settled one). Two cautions are load-bearing. First, this tradition classes crystals among the “trivial” replicators — highly compressible, periodic, low in life-like information [5]; any crystalline-life proposal must clear the bar of carrying non-trivial, low-compressibility information. Second, defining objects by formation history [6] makes precise the sense in which a crystal can record its past in its geometry — but recording a history is not the same as evolving, a distinction we return to.

5. Growth from within: the twist as engine and memory

Crystal growth is usually surface accretion, but one mode is organized from within and is foundational. Burton, Cabrera, and Frank built modern crystal-growth theory on the recognition that a screw dislocation — an internal line defect, a twist in the lattice — continually extrudes growth steps; the step cannot detach from the dislocation, so it winds around it in a perpetual spiral, advancing the face without nucleating fresh layers

[7]. The internal twist is thus both the thing that persists, threaded through the crystal's core, and the engine that regenerates the layer pattern. In a screw-dislocation crystal the stored state and the copying process are the same feature — provided the defect is metastable or topologically protected, so reverting it requires crossing an energy barrier rather than simply relaxing. Such protected defects are exactly those that escape the fidelity wall of §3.

6. Writing and propagating the twist

What writes a twist is stress, recorded at a threshold. In epitaxy, strain accumulates as a mismatched film thickens — held elastically, reversibly — until a critical thickness, at which dislocations nucleate to relax it [13]; below threshold nothing permanent is written, above it a defect is created and the strain relieved, and the sign of the stress leaves a distinguishable mark. Events also write twists: a screw dislocation can be born from the lattice mismatch where two crystals coalesce. Once written, the defect propagates forward through every growth layer by the spiral mechanism of §5, and growth zoning logs the conditions at each stage, as tree rings do. The seam to mark plainly: a threshold-triggered, forward-propagating, environmentally-logged structural change supplies sensing, writing, persistence, and a record — but a medium that records is not yet a lineage under selection.

7. The flaw as a triple-duty part

Consider a rotational defect made by the Volterra construction: cut the crystal along a line, remove or insert a wedge — a pie slice — and weld the lips, forcing a rotation. This is a disclination, the rotational sibling of the screw dislocation; a dislocation is itself a dipole of two opposite disclinations [11]. We propose such a protected defect as a candidate minimal biological part because it performs three functions in one feature.

The triple-duty topological defect (central conjecture)

Memory. A topologically protected disclination cannot relax to the perfect lattice without crossing an energy barrier; it stores anneal-resistant state — the property the mineral-life program lacked.

Morphogen. The defect concentrates curvature: a removed wedge puckers the sheet into a cone, an added wedge into a saddle — the mechanism by which five- and seven-fold defects curl flat lattices like graphene. The stored state shapes the form.

Transducer. The defect is a concentrated strain gradient, and a strain gradient breaks centrosymmetry locally, producing polarization by flexoelectricity — allowed in any symmetry, even centrosymmetric crystals with no piezoelectricity [12]. The flaw becomes a local source of electrical signal.

If these coincide in one protected defect, a crystalline proto-organism need not bolt separate gene, body plan, and signalling system onto an inert lattice — one multi-duty part could be all three. Caveat, on the page: isolated disclinations are high-energy in bulk crystals; they appear mainly in two-dimensional materials, thin films, and

nanostructures, or where the crystal curves up into a cone, tube, or shell. We treat this as a prediction — the flaw forces a three-dimensional form — not a refutation.

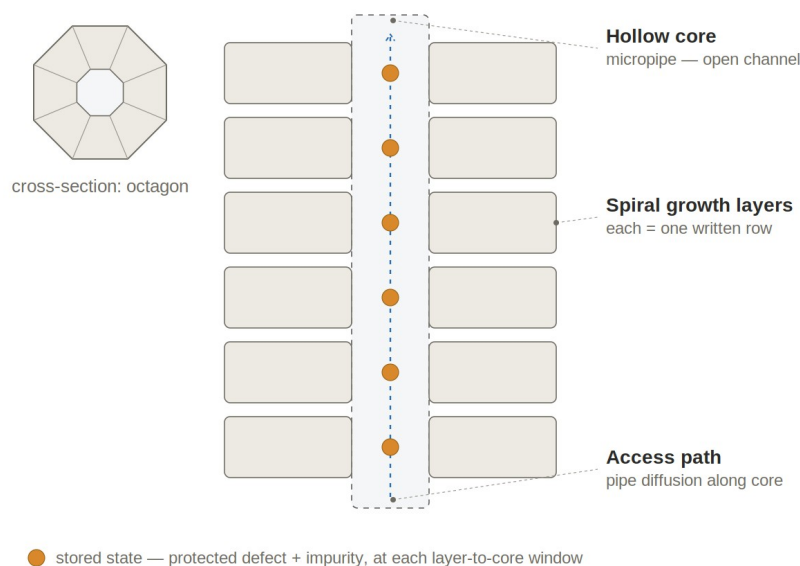


Figure 1. A hollow-core screw-dislocation spiral as a layered memory. The twist (a large-Burgers screw dislocation) opens a hollow core — a Frank micropipe [17] — that threads every spiral growth layer. Each layer holds a protected defect-state at the point where it meets the core (the “window”); the open core is the access path. Inset: octagonal cross-section (eight-fold symmetry places it in quasicrystal territory).

8. Reading, writing, and the capacity of a cross-section

A stored state must be addressable, and two established channels match two kinds of bit. If the state is structural — a strain or defect — the read/write is piezoelectric and flexoelectric: an applied voltage strains the lattice (write), a strain produces a voltage (read), and at the defect the strain-gradient flexoelectric coupling gives a signal even in a centrosymmetric crystal [12]. If the state is a spin — a magnetic defect such as a colour centre — the channel is radiofrequency magnetic resonance, the physics that reads spin qubits. The hollow core supplies the wiring: a hollow channel is a waveguide (hollow tubes guide microwaves, hollow-core fibres guide light), so the central pipe can carry the interrogation field with no filler, while mechanical signals travel in the surrounding lattice. No exotic transmission medium is required — fields need none, phonons use the lattice.

The recording capacity of each cross-section follows from information theory. If the section is partitioned into N independently distinguishable sub-cells (the “triangles” of a sectorized octagon) and each holds L distinguishable states — multilevel storage, already routine in phase-change and memristive cells [8], with an optical/colour readout such as switchable circular dichroism as one realisation of a multi-state “colour” channel — the capacity is about $N \times \log_2(L)$ bits per layer. More triangles, and more colours per triangle, raise density: the areal-density $\times$ multilevel product that drives all storage. A quasicrystalline (octagonal) tiling helps, because its aperiodic order can carry non-trivial, low-compressibility information across the section in a way a periodic tiling

cannot — clearing the bar of \$4. The hard ceiling is distinguishability: pack the triangles or colour levels too tightly and crosstalk merges them, capping usable capacity below the geometric one — the binning / signal-to-noise wall. Finally, the seamless stacking that lets layers fuse is not arbitrary: particular commensurate “coincidence” angles — the moiré / magic angles of twisted layers [18] — are where lattices match at low energy (Figure 2).

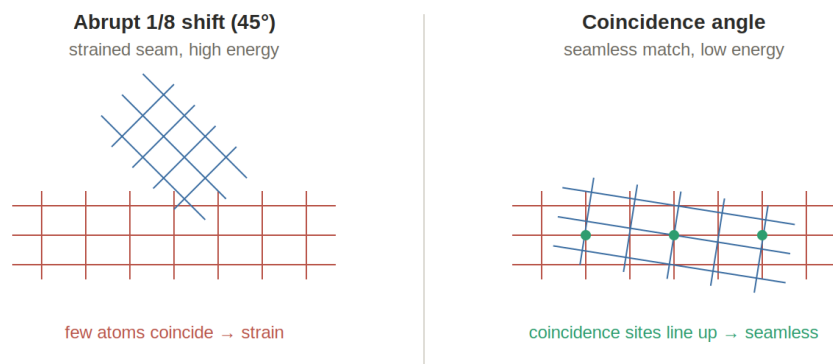


Figure 2. Why the stacking angle matters. An abrupt 1/8 (45°) shift leaves few atoms coincident and a strained, high-energy seam (left); a commensurate coincidence angle lines up periodic coincidence sites for a seamless, low-energy match (right). Choosing a coincidence/moiré angle [18] is how stacked layers fuse cleanly.

9. Branching morphology as a substrate-independent phenomenon

Crystal and organism can share form as one named phenomenon, not analogy. Tree-shaped crystals are dendrites; dendritic growth is the branched development of a crystal into an undercooled or supersaturated medium, modelled by diffusion-limited aggregation [9] — a tip reaching into a richer supply outpaces flat regions, so bumps amplify into branches. The same process governs snowflakes, mineral dendrites, rivers, lightning, and biological branching. Strikingly, a diffusive-growth model reproduces realistic neuronal dendritic morphologies with almost no stored program [14], its authors concluding that complex reproducible trees need no intrinsic plan of the geometry — substrate independence demonstrated inside biology. The open question is not whether the forms match (they do) but how much program rides on the shared physics.

10. The proto-organism as agent: displacing and engulfing

A growing crystal acts on its surroundings in two regimes that map onto familiar images. Displacing — a root cracking a foundation — is crystallization pressure: salt and ice crystals growing in confinement push grains apart and break rock, a force measured directly at the microscale [10]; frost heave damages roads, salt weathering has destroyed monuments, and the crucial condition is confinement (a crystal with room does not shove; a confined one does). Engulfing — a tree growing around a fence — is the pushing-versus-trapping of a growth front meeting a particle, which it either routes around or captures as an inclusion depending on growth velocity; the captured object is frozen permanently into the record.

11. Selection, not recording: where the environmental information lives

The substrate need not record its environment at all. A replicator copies itself; the environment writes by filtering which variants continue to copy, so the information about the environment resides in the composition of the surviving population, not in any individual's log. Natural selection is, in this exact sense, the accumulation of environmental information into the replicator population [19], measurable as the divergence of the population's state distribution from the neutral one. This dissolves the recorder-versus-memory tension: the substrate should optimise for fidelity, not sensitivity, and the environmental fit arrives through selection, for free, at the population level. The requirement this smuggles in — and it is the hard one — is a population of heritable variants whose differences are consequential for replication. Without that, “it replicated” is growth, not selection, and no information accumulates.

12. The substrate as a self-healing network

The architecture is fault-tolerant by the same principle as topological quantum memory. Information stored in a non-local topological invariant is robust to local perturbation: there is no local order parameter for noise to corrupt, so the encoded state survives local damage and can change only through a global, barrier-crossing event [16]. That is self-correction by construction. Redundancy across the repeating layers adds a second healing mechanism — a corrupted layer can be reconstructed from the others, as an error-correcting code or a fault-tolerant network reroutes around a failed node. And the self-healing has a precise limit: it is the Eigen error threshold [15], the maximum copying-error rate below which information is maintained and above which it collapses into error catastrophe. Self-healing and the error threshold are one phenomenon seen twice. The caveat is essential: ordinary material self-healing (annealing) repairs a crystal by erasing defects, which would erase the memory; the architecture can heal and remember only because the bits are topological, so local repair of the bulk leaves the non-local invariant untouched.

13. Testable predictions and connections to other fields

The synthesis earns engagement only if it can be broken. The following are concrete, on platforms that exist today. The individual ingredients are established; the two bridges under test — topological protection as the fix for the fidelity wall, and an Eigen error threshold for a crystalline replicator — are, as far as we know, novel as claims and should be treated as hypotheses to check, not as results.

- **Fidelity, protected vs. unprotected.** Across growth-fragmentation-regrowth cycles, a topologically protected defect should be inherited with far higher fidelity than an impurity pattern. Platform: algorithmic DNA-tile crystals [4], which already replicate combinatorial information with measurable fidelity, or micropipe defects in SiC/GaN by X-ray topography [17].
- **The error threshold (quantitative headline).** Tune the copying-error rate and look for the predicted error catastrophe — a critical fidelity below which heritable defect-information collapses [15]. Prediction: topological protection moves the system from below to above threshold.

- **Triple-duty coincidence.** On a single disclination (graphene) or micropipe (SiC), read curvature (AFM/TEM), strain (Raman), and flexoelectric polarization (piezoresponse force microscopy) and show the three co-report one state. Independence would falsify the “one part, three duties” claim.
- **Selection, not recording.** In a population of heritable defect-variants under a differential-replication pressure, measure whether the population composition shifts toward the favoured variant, quantified as increasing divergence from the neutral distribution [19]. A positive result is the first demonstration of selection on a crystal substrate.
- **Cross-domain modelling.** Treat the crystalline replicator as a formal quasispecies and apply population-genetics tools — error threshold, Muller’s ratchet, mutation-selection balance [15] — bridging materials science and evolutionary genetics. Compare crystal-dendrite and neuronal/vascular branching statistics [9,14] to test how much program rides on shared physics.

14. Open seams

The load-bearing weaknesses this draft does not resolve, collected:

- **Replication is not yet selection.** Copying is easy and crystals do it; selection requires a population of heritable variants whose differences change replication success. This, not “recording,” is the principal seam.
- **The fidelity wall is reframed, not cleared.** Protected defects are argued to resist annealing, but no demonstration of high-fidelity heritable defect copying in a non-DNA substrate is offered here.
- **The trivial-replicator bar is unmet.** We assert that quasicrystalline substrates could carry non-trivial information; we do not show it.
- **Bulk energetics.** The triple-duty disclination is natural in low dimensions or curved geometries, not flat bulk; the proposal may be confined to 2D / thin-film / nanostructured regimes.
- **Convergence is asserted, not derived.** That the same organization recurs across substrates is argued from examples, not proven from the minimal-agent constraints invoked.

15. Conclusion: an invitation

This is a draft written to start an argument. Its contribution is the juxtaposition — artificial life’s substrate independence, the mineral tradition’s ambition and its fidelity wall, the information-theoretic account of what is conserved, the defect physics of crystals, and the quasispecies error threshold — placed at one table, plus two falsifiable bridges: that topological protection fixes crystalline heredity’s fidelity problem, and that such a replicator has a measurable error threshold. The modest claim is that a protected lattice defect can store state, shape form, emit signal, and resist local error — all in established physics. The provocative claim, fenced, is that such a part could seed a non-carbon living organization. Released freely (CC BY 4.0) so anyone can take it further — perhaps toward better storage, perhaps toward a problem we haven’t imagined — we

invite disagreement, and especially the experiment that draws the line between a crystal that remembers and a crystal that lives.

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Citation note: references [4][5][6][7][8][9][10][12] are grounded directly in sources reviewed for this draft. References [1][2][3][11][13][14][15][16][17][18][19][20] are standard works cited from established literature; verify each against the original (especially years, volumes, and the neuronal-DLA and oscillatory-zoning attributions) before external circulation.

Referee Report

Rolling review and change log (v1 → v2)

Reviewer stance: skeptical but fair. Doubles as the version tracker.

Summary judgment

Judged as a synthesis/position paper, v2 is materially stronger than v1: it now states two falsifiable bridges, gives a quantitative headline prediction (the error threshold), and proposes concrete experiments on real platforms. The recurring discipline of separating recording from evolving, and grounded physics from conjecture, remains the paper's backbone. Recommendation: defensible as a speculative, openly-licensed position paper; not an empirical claim; the novelty resides in the two bridges and should be presented as hypotheses pending a literature check and the proposed experiments.

What v2 changed

- Added §13 (testable predictions) with five concrete tests and named platforms — addresses the v1 concern that the work risked being non-falsifiable.
- Added §11 (selection, not recording), reframing the principal seam: the substrate need not record; selection accumulates environmental information into the population. Seam #1 rewritten accordingly.
- Added §12 (self-healing network), unifying topological protection, redundancy, and the Eigen error threshold as one fault-tolerance story.
- Added §8 (reading/writing and cross-section capacity), the addressing channels and the information-capacity argument; Figures 1 and 2 added.
- Promoted the Eigen error threshold to the quantitative headline prediction; added quasispecies, topological-QEC, hollow-core, coincidence-angle, and selection-as-information references.

Remaining major concerns (for v3)

- **Selection is proposed, not modelled.** §13 gives an experiment but no toy model. A minimal mathematical model showing heritable defect-variants under a fitness difference would convert the central claim from hope to mechanism.
- **The triple-duty coincidence is argued by listing three true facts.** v3 should argue that one defect can satisfy all three demands simultaneously — e.g. deep-well stability versus modulable flexoelectric output — not merely each in isolation.

- **Citations require verification.** Several are from standard knowledge; confirm [1][2][3][11][13][14][15][16][17][18][19][20] before circulation.
- **Convergence still asserted.** Derive cross-substrate recurrence from the minimal-agent constraints, or keep it explicitly labelled conjecture.

Change log

v1 — baseline established; sections frozen as the reference snapshot; five open seams recorded.

v2 — added §8, §11, §12, §13 and Figures 1-2; rewrote seam #1; promoted the error-threshold prediction; expanded references; adopted CC BY 4.0. Open items for v3: toy selection model; triple-duty compatibility argument; citation verification; derivation of convergence.

— end of v2 snapshot and referee report —