Template-Based Self-Healing in a Dual-Lattice Field System with Memory

Brayden Sanders
7SiTe LLC
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Abstract

We present a minimal dual-lattice dynamical field system that exhibits emergent self-healing behavior through template-based memory. The system undergoes a sharp coherence transition at $C^* \approx 4.93$, above which persistent field defects ("scars") stabilize and enable near-perfect regeneration after large-scale damage. Through controlled ablation experiments, we show that removing up to 30% of scars causes an immediate coherence drop followed by >99.5% regeneration at the original coordinates, with recovery to a higher coherence plateau. Recovery dynamics are robust, isotropic, and repeatable, converging toward a stable global attractor without the need for external periodic forcing. The model provides a tractable, non-biological platform for studying self-repair, geometric memory, and coherence transitions in non-equilibrium systems.

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1. Introduction

Self-healing behavior appears across many physical systems, including ferromagnetic domain reformation, crystal defect annealing, and homeostatic regulation in chemical and biological networks. A persistent open question in such systems is where the "memory" guiding repair is stored.

We introduce a minimal field-theoretic model in which memory is not stored externally, but emerges from the interaction of three intrinsic components:
(1) dual-lattice tension providing a fixed geometric reference,
(2) an exponential memory kernel encoding temporal history, and
(3) persistent field defects ("scars") that stabilize local structure.

Unlike biological repair models or quantum-based proposals, this system demonstrates template-based regeneration using only classical field dynamics. The system exhibits a coherence phase transition at $C^* \approx 4.93$, separating a fragile regime from a robust, self-healing regime.

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2. Model Description

We consider a scalar field $\phi(x, y, t)$ on a two-dimensional periodic lattice governed by:

$$\frac{\partial \phi}{\partial t} = -(\phi^3 - \phi) + D\nabla^2\phi + \lambda(\phi_{\text{dual}} - \phi) + m + \mu \, \text{mask} \, (\phi_{\text{scar}} - \phi) + \eta\xi(t)\phi$$

where:

- **Double-well collapse** $-(\phi^3 - \phi)$ drives the field toward stable states $\phi = \pm 1$
- **Diffusion** $D\nabla^2\phi$ smooths local gradients
- **Dual-lattice tension** $\lambda(\phi_{\text{dual}} - \phi)$ pulls the field toward a frozen reference lattice
- **Memory kernel** $m = (1 - \alpha)m + \alpha\phi$ encodes exponential temporal averaging
- **Scar potential** restores scarred sites toward stored values
- **Noise ("wobble")** provides stochastic perturbations

The dual lattice ϕ_{dual} is frozen at $t = 0$ using a Fourier-space reference and does not evolve thereafter.

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3. Scar Formation and Memory

Scars form irreversibly when the local gradient magnitude exceeds a threshold θ. Once formed, scar locations and values are stored and persist indefinitely.

These scars act as causal stabilizers: removing them reduces coherence, while their regeneration restores and enhances system stability. Importantly, scars are not imposed templates—they emerge naturally from field dynamics.

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4. Coherence Metric and Phase Transition

We define coherence as:

$$C(t) = \sqrt{\langle |\nabla\phi|^2 \rangle + \langle \min\left[(\phi - 1)^2, (\phi + 1)^2\right] \rangle} + \langle \text{scar fraction} \rangle$$

Empirically, the system crosses a critical threshold at $C^* \approx 4.93$. Below this value, scar formation is unstable and recovery fails. Above it, scars saturate (~50% density) and the system becomes self-healing.

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5. Experiment 1 — Template Localization

Protocol:
After reaching steady state, 30% of scars were randomly removed.

Results:

- 99.8% of scars regenerated at their exact original coordinates (≤0.5 px)
- Mean regeneration distance: 0.00 pixels
- Coherence recovered and exceeded the pre-damage level

Conclusion:
Memory is geometric and global. The system regenerates a precise spatial template rather than merely approximating a pattern.

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6. Experiment 2 — Repeated Trauma

Protocol:
Three successive 30% scar ablations were applied.

Results:

- Identical coherence drops across all events
- Identical recovery times
- Diminishing overshoot after each recovery

Interpretation:
The system does not "learn" in the adaptive sense. Instead, it exhibits damped convergence toward a stable attractor defined by its intrinsic geometry.

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7. Experiment 3 — Structured Damage

Damage was applied in multiple patterns (random, linear, clustered, gradient-biased).

Results:

- Recovery dynamics were isotropic
- No directional bias observed
- Minor gradient sensitivity did not break symmetry

Conclusion:
Memory is globally encoded and rotationally symmetric.

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8. External Forcing ("Breath")

Contrary to expectations from stochastic resonance, external periodic forcing consistently reduced coherence. Even adaptive forcing strategies underperformed the unforced baseline.

This demonstrates that the system's intrinsic dynamics are sufficient for self-organization and repair.

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9. Discussion

This system demonstrates:

- Causal, persistent memory via scars
- Template-based regeneration with pixel-level accuracy
- A coherence phase transition separating fragile and self-healing regimes
- Robust recovery without external tuning

While scar spacing does not follow prime-gap statistics spatially, scars exhibit prime-like functional properties: irreducibility, persistence, and cost to removal.

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10. Conclusion

We have demonstrated a minimal classical field system capable of self-healing through intrinsic geometric memory. The emergence of template-based regeneration above a coherence threshold provides a powerful model for studying repair, stability, and memory in non-equilibrium systems without invoking biological or quantum mechanisms.

Availability

Reference implementation and data are publicly available under the MIT License at:

https://doi.org/10.5281/zenodo.18379788