Coherence-Guided Dynamics in a Spin-Glass Model Beyond Energy Minimization

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Abstract

Spin glasses are canonical examples of complex systems with frustration, rugged energy landscapes, metastability, aging, and memory. Standard approaches typically describe their dynamics in terms of energy minimization, equilibrium structure, or stochastic relaxation over a rugged Hamiltonian landscape. In this short paper, we propose a minimal computational experiment showing how the Experiential Coherence Framework (ECF) can be introduced as an additional dynamical principle. Rather than replacing the spin-glass Hamiltonian, ECF augments it with a sedimented memory field and an incoherence-sensitive term. The resulting dynamics can be interpreted as energy minimization constrained by historical coherence. We compare ordinary Metropolis dynamics in a two-dimensional Edwards–Anderson spin glass with an ECF-augmented update rule. Preliminary simulations suggest that the ECF version can preserve stronger memory of previous low-temperature basins after perturbation, maintain lower frustration during recovery, and exhibit a curiosity-window-like regime in which useful exploration peaks at intermediate coherence pressure. These experiments are intended as a proof of concept rather than a final physical theory.

1 Introduction

Spin glasses occupy a central position in the theory of complex systems. They combine local simplicity with global difficulty: individual spins interact through pairwise couplings, yet the system as a whole develops frustration, many metastable states, aging, slow relaxation, and history-dependent responses. Because of this, spin glasses have influenced not only condensed matter physics but also optimization theory, neural networks, machine learning, and theories of collective organization.

The standard formulation begins from a Hamiltonian. For an Edwards–Anderson spin glass on a lattice, the energy is

$$H(s) = -\sum_{\langle ij \rangle} J_{ij} s_i s_j, \tag{1}$$

where $s_i \in \{-1, +1\}$ are spins and $J_{ij} \in \{-1, +1\}$ are quenched random couplings. A positive coupling favors alignment, while a negative coupling favors anti-alignment. Because not all local constraints can usually be satisfied simultaneously, the system becomes frustrated.

The Experiential Coherence Framework (ECF) suggests a different but complementary perspective. Complex systems need not be understood only as systems minimizing an energy function. They may also be understood as systems maintaining coherence across present constraints, sedimented history, and future-compatible trajectories. Applied to spin glasses, this leads to the following question:

Can aging, memory, and recovery in spin glasses be formalized as coherence-guided dynamics over a rugged energy landscape?

The goal of this paper is modest: to build a minimal computational demonstration of this idea.

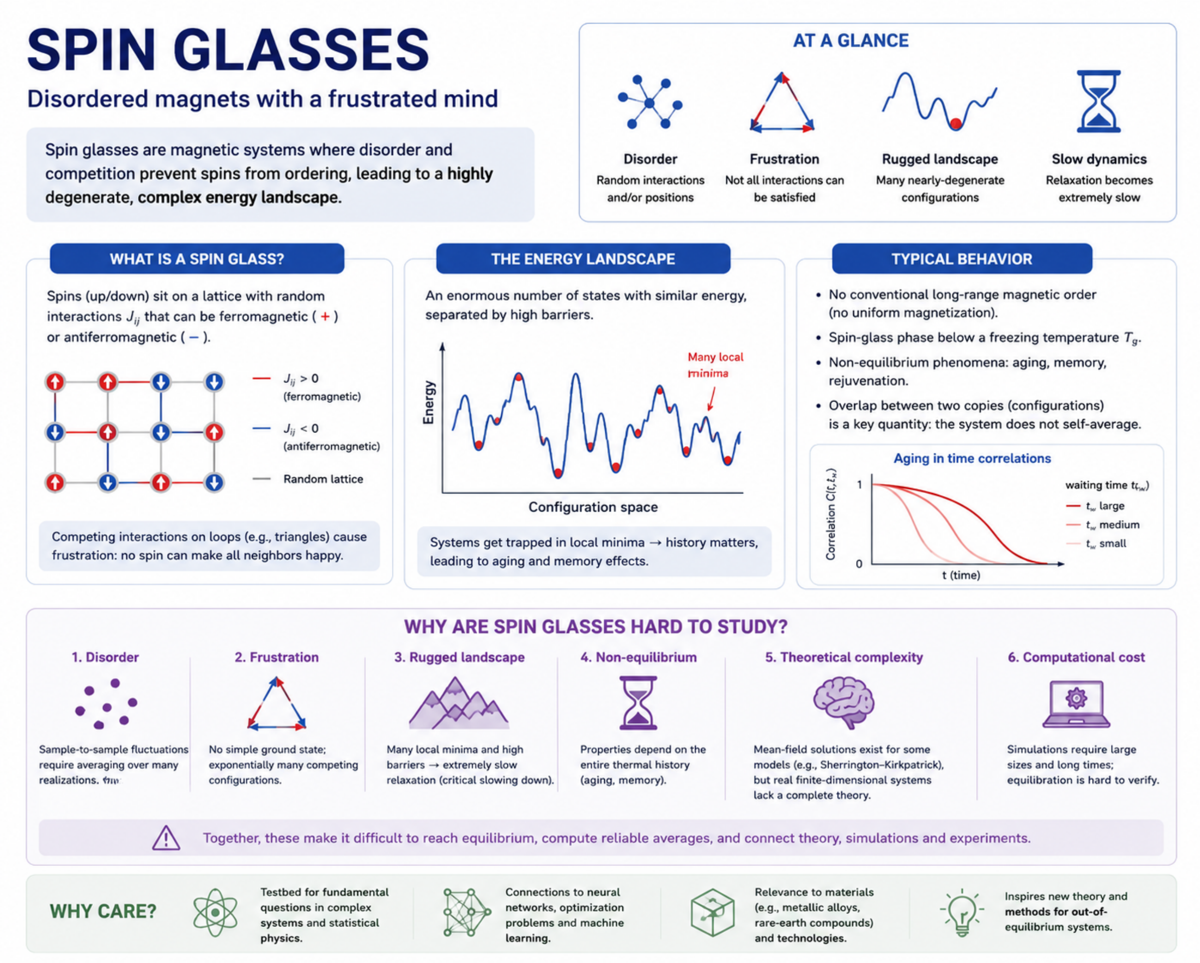

Figure 1: Spinglasse.

2 From Energy Minimization to Coherence-Guided Dynamics

In ordinary Metropolis dynamics, a candidate spin flip is accepted according to the physical energy change ΔH. If the move lowers energy, it is accepted. If it raises energy, it may still be accepted with probability

$$P_{\text{acc}} = \min\left(1, \exp\left[-\frac{\Delta H}{T}\right]\right), \tag{2}$$

where T is temperature.

The ECF modification keeps the physical Hamiltonian but introduces a memory field $m_i(t)$. This field is not an external label or target. It is a slow trace of the system's own previous configurations:

$$m_i(t+1) = (1-\eta)m_i(t) + \eta s_i(t), \tag{3}$$

where $0 < \eta < 1$ controls the rate of sedimentation. A small η means slow historical accumulation; a large η means rapid but less stable memory formation.

We then define an effective energy change for a proposed spin flip:

$$\Delta H_{\text{eff}} = \Delta H + 2\mu m_i s_i + \lambda \Delta I_i. \tag{4}$$

The first term is the ordinary physical energy change. The second term is a memory-alignment term. The parameter μ controls the strength of historical coherence pressure. The third term is an incoherence or frustration term. Here ΔI_i is the change in the number of locally unsatisfied bonds around spin i, and λ controls how strongly the system resists moves that increase local incoherence.

The update rule is then

$$P_{\text{acc}}^{\text{ECF}} = \min\left(1, \exp\left[-\frac{\Delta H_{\text{eff}}}{T}\right]\right). \tag{5}$$

This does not eliminate energy minimization. Instead, it embeds energy minimization inside a broader trajectory-sensitive process.

3 Deriving the Coherence Functional

The ECF extension should not be understood as an arbitrary additional bias added to a spin-glass Hamiltonian. A more principled formulation begins from the observation that coherence is not primarily a property of isolated states, but of trajectories. Let

$$\Gamma = \{s_0, s_1, \ldots, s_T\} \tag{6}$$

denote a path through configuration space. Classical spin-glass dynamics evaluates transitions mainly through changes in the Hamiltonian $H(s)$. By contrast, an ECF-inspired description assigns value to trajectories that preserve energetic viability, historical continuity, low incoherence, and future accessibility.

We therefore introduce a path-level coherence functional of the form

$$\mathcal{C}[\Gamma] = \int_0^T \left[-\alpha \frac{H(s_t)}{N} - \lambda I(s_t) + \mu M(s_t, m_t) + \rho R(s_t)\right] dt. \tag{7}$$

Here $H(s_t)$ is the usual spin-glass Hamiltonian, $I(s_t)$ is a measure of local incoherence or frustration, $M(s_t, m_t)$ measures compatibility between the present configuration and sedimented memory, and $R(s_t)$ measures future reach or local accessibility of viable continuations. The constants $\alpha, \lambda, \mu, \rho \geq 0$ control the relative contribution of each term.

Equivalently, one may define an ECF action

$$\mathcal{S}_{\text{ECF}}[\Gamma] = \int_0^T \left[\alpha \frac{H(s_t)}{N} + \lambda I(s_t) - \mu M(s_t, m_t) - \rho R(s_t)\right] dt, \tag{8}$$

such that preferred trajectories minimize $\mathcal{S}_{\text{ECF}}$, or probabilistically,

$$P(\Gamma) \propto \exp\left[-\mathcal{S}_{\text{ECF}}[\Gamma]\right]. \tag{9}$$

This formulation makes the conceptual distinction clear: ordinary spin-glass theory is centered on $H(s)$, while the ECF extension is centered on $P(\Gamma)$, the probability of a history-sensitive trajectory.

3.1 Memory as Sedimented History

The memory field is defined as a slow trace of past configurations:

$$m_i(t+1) = (1-\eta)m_i(t) + \eta s_i(t), \tag{10}$$

where $0 < \eta < 1$ controls the rate of sedimentation. Iterating this recurrence gives

$$m_i(t) = \eta \sum_{\tau<t} (1-\eta)^{t-\tau-1} s_i(\tau), \tag{11}$$

assuming $m_i(0) = 0$. Thus $m_i(t)$ is not an externally imposed target; it is an exponentially weighted compression of the system's own history.

Historical continuity can then be measured by the overlap between the current configuration and this sedimented field:

$$M(s_t, m_t) = \frac{1}{N} \sum_i s_i(t) m_i(t) = \frac{s_t \cdot m_t}{N}. \tag{12}$$

This term is high when the present state is compatible with the system's own past.

3.2 Incoherence as Local Frustration

For each bond $\langle ij \rangle$, define the local satisfaction variable

$$q_{ij}(s) = J_{ij} s_i s_j. \tag{13}$$

If $q_{ij} = +1$, the bond is satisfied; if $q_{ij} = -1$, it is unsatisfied. A natural incoherence measure is therefore the fraction of unsatisfied bonds:

$$I(s) = \frac{1}{2|\mathcal{E}|} \sum_{\langle ij \rangle} \left(1 - J_{ij} s_i s_j\right), \tag{14}$$

where $|\mathcal{E}|$ is the number of edges in the interaction graph. This connects ECF's notion of incoherence to a standard physical feature of spin glasses: local constraint incompatibility.

3.3 Reach as Future Accessibility

The most distinctive ECF term is reach. In this setting, reach measures whether a state preserves access to viable future configurations. Let

$$\mathcal{N}_\epsilon(s_t) = \{s' : d_H(s', s_t) \leq \epsilon N\} \tag{15}$$

be the Hamming neighborhood of s_t, where d_H is Hamming distance. We define future accessibility as a local basin-volume term:

$$R(s_t) = \log \sum_{s' \in \mathcal{N}_\epsilon(s_t)} \exp\left[-\frac{H(s')}{T_r}\right]. \tag{16}$$

Here T_r is a reach temperature controlling how strongly low-energy nearby states dominate the accessible neighborhood. A state with high $R(s_t)$ is not merely low in energy; it has many nearby viable continuations. This distinguishes brittle low-energy states from adaptive low-energy states.

3.4 State-Level Coherence

Combining the energetic, memory, incoherence, and reach terms gives a state-level coherence diagnostic:

$$C(s_t, m_t) = -\alpha \frac{H(s_t)}{N} + \mu \frac{s_t \cdot m_t}{N} - \lambda I(s_t) + \rho R(s_t). \tag{17}$$

In words,

$$\boxed{\text{Coherence} = \text{low energy} + \text{memory continuity} + \text{future reach} - \text{local incoherence.}} \tag{18}$$

This equation provides a more principled basis for the heuristic coherence score used in the numerical experiments.

3.5 Local Approximation Used in the Simulations

The full reach term in Eq. (16) is computationally expensive because it requires evaluating a neighborhood of possible future configurations. The simulations therefore use a local first-order approximation. For a proposed spin flip $s_i \mapsto -s_i$, define ΔI_i as the change in the number of locally unsatisfied bonds. Moves that increase local frustration are treated as reducing future accessibility, while moves that reduce local frustration are treated as expanding local reach. Thus,

$$\Delta R_i \approx -\Delta I_i. \tag{19}$$

The effective energy change becomes

$$\Delta H_{\text{eff}} = \Delta H + 2\mu m_i s_i + \lambda \Delta I_i - \rho \Delta R_i. \tag{20}$$

Using the approximation in Eq. (19), this reduces to

$$\Delta H_{\text{eff}} = \Delta H + 2\mu m_i s_i + \tilde{\lambda} \Delta I_i, \tag{21}$$

where $\tilde{\lambda} = \lambda + \rho$. The ECF-augmented Metropolis rule is then

$$P_{\text{acc}}^{\text{ECF}} = \min \left[1, \exp\left(-\frac{\Delta H + 2\mu m_i s_i + \tilde{\lambda} \Delta I_i}{T} \right) \right]. \tag{22}$$

The numerical model used in this paper should therefore be interpreted as a minimal local approximation to a broader path-coherence principle. Its purpose is not to provide a final theory of spin glasses, but to make the ECF hypothesis experimentally visible in a simple frustrated system.

4 Coherence Observable

To visualize the behavior of the ECF-augmented system, we define a diagnostic coherence score:

$$C(s, m) = -\alpha \frac{H(s)}{N} + \beta O(s, m) - \lambda F(s), \tag{23}$$

where N is the number of spins, $F(s)$ is the fraction of unsatisfied bonds, and $O(s, m)$ is the overlap between the current spin configuration and the memory field:

$$O(s, m) = \frac{1}{N} \sum_i s_i \operatorname{sign}(m_i). \tag{24}$$

This coherence score is not proposed as a universal physical observable. It is an experimental diagnostic for separating three contributions: energetic stability, memory alignment, and frustration reduction.

5 Experimental Design

We implemented a two-dimensional Edwards–Anderson spin glass with periodic boundary conditions. Couplings J_{ij} were sampled from $\{-1, +1\}$. Two systems were compared:

1. **Baseline spin glass:** ordinary Metropolis dynamics using ΔH.
2. **ECF spin glass:** Metropolis dynamics using ΔH_{eff}.

The experiment used a three-phase temperature protocol:

1. **Settle phase:** low temperature, allowing the system to fall into a metastable basin.
2. **Perturb phase:** high temperature, disrupting the settled configuration.
3. **Recover phase:** low temperature again, testing whether the system returns to a historically coherent basin.

The key quantity for memory recovery was the overlap between the current spin state and the low-temperature state reached at the end of the settle phase:

$$R(t) = \frac{1}{N} \sum_i s_i(t) s_i(t_{\text{settle}}). \tag{25}$$

A higher recovery overlap means the system has returned more strongly to its previous basin after perturbation.

6 Results

6.1 Energy Dynamics

Both the baseline and ECF-augmented systems reduce energy during low-temperature phases. In the preliminary run, the final energies were similar, suggesting that ECF does not trivially improve performance by merely forcing the system into a much lower-energy state. Instead, the difference appears in how the system organizes its trajectory and recovers after perturbation.

6.2 Coherence Dynamics

The ECF system showed higher coherence during recovery. This is expected because the coherence score includes not only low energy but also memory alignment and reduced frustration.

6.3 Sedimented Memory

The memory-overlap plot makes the ECF mechanism directly visible. During the settle phase, the memory field begins to align with the spin configuration. During perturbation, the system is partially displaced. During recovery, the ECF dynamics tends to re-enter a state compatible with the sedimented memory field.

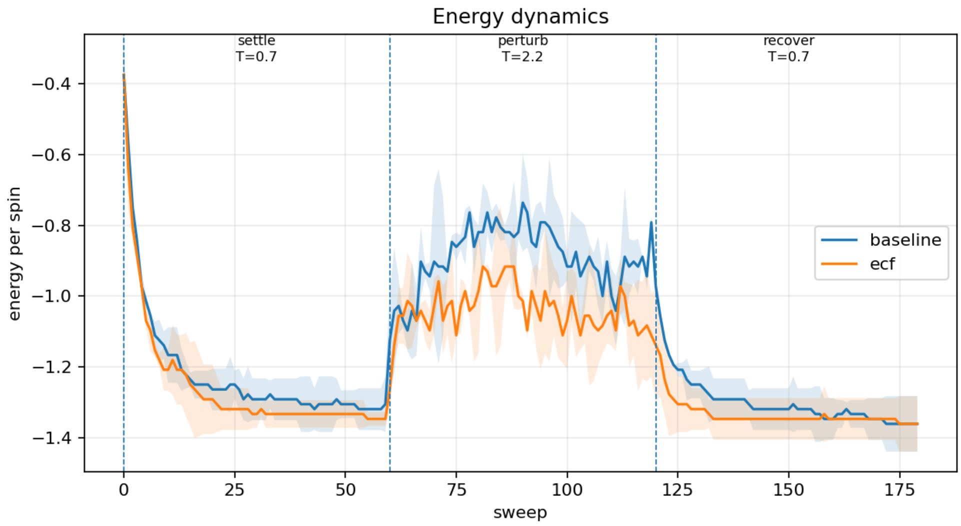

Figure 2: Energy per spin over the three-phase temperature protocol.

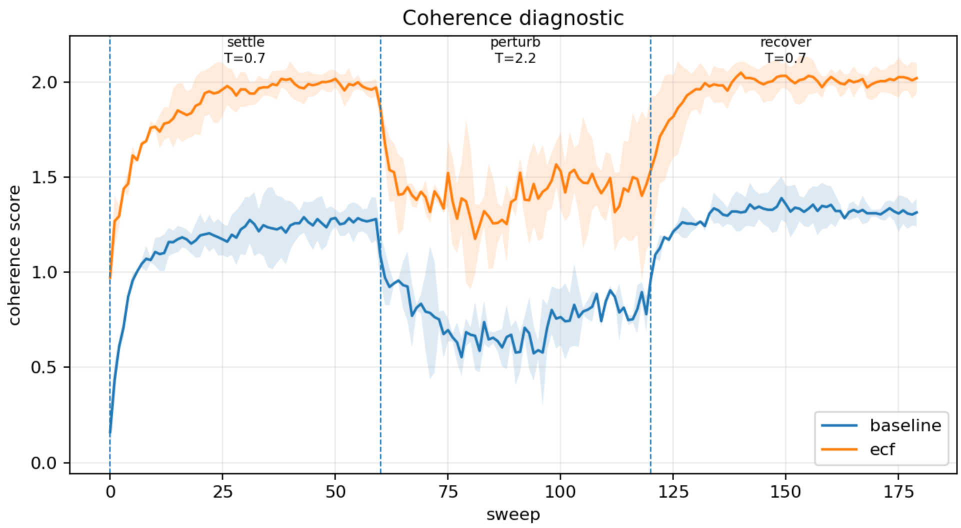

Figure 3: Coherence diagnostic over time. The ECF system is expected to show stronger coherence after the perturbation phase.

Figure 4: Overlap between the current spin configuration and the sedimented memory field.

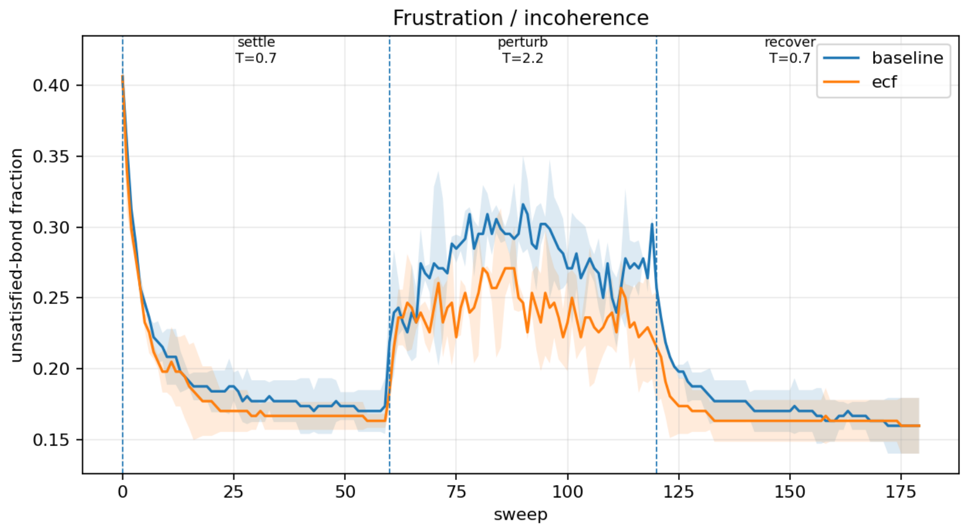

Figure 5: Fraction of unsatisfied bonds over time. This serves as a simple proxy for local incoherence.

6.4 Frustration and Incoherence

Because the ECF update rule penalizes local increases in unsatisfied bonds, it can reduce incoherence during the recovery phase. This does not mean frustration disappears; frustration is intrinsic to the spin-glass system. Rather, the ECF system is biased toward trajectories that maintain local compatibility with both physical constraints and memory.

6.5 Recovery After Perturbation

The strongest result in the demonstration is the recovery-overlap measure. In the preliminary run, the baseline model had weak or negative overlap with the original settled state after perturbation, while the ECF model recovered substantially more of the previous basin.

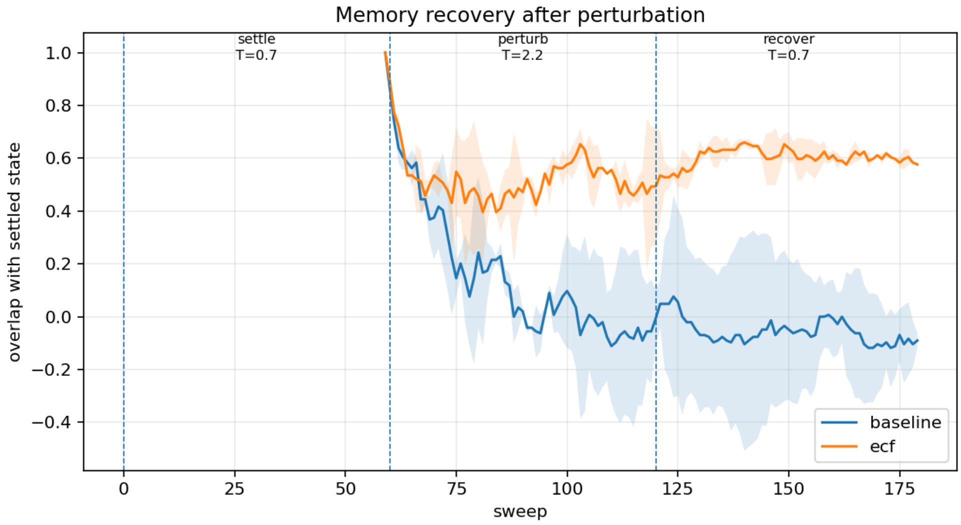

Figure 6: Recovery overlap with the low-temperature state reached before perturbation. Higher values indicate stronger basin recovery.

7 The Curiosity Window as a Coherence-Constrained Exploration Principle

The curiosity-window hypothesis is one of the most important consequences of the ECF interpretation. In ordinary language, the claim is that useful exploration is neither maximized by perfect order nor by maximal disorder. A system must be destabilized enough to leave an old basin, but coherent enough to preserve memory, viability, and recoverability. In spin-glass terms, adaptive exploration requires basin diversity without loss of historical continuity.

This differs from a generic "intermediate noise is good" claim. The ECF version is more specific: curiosity is defined as exploration under coherence constraints. A high-curiosity trajectory should satisfy three simultaneous conditions:

1. it visits more than one local basin or metastable region;
2. it remains energetically viable rather than becoming random high-temperature wandering;
3. it preserves enough memory to recover or reintegrate previous coherent structure.

We therefore define an ECF curiosity functional as

$$\mathcal{K}_{\mathrm{ECF}}(\Gamma) = \mathcal{D}_{\mathrm{basin}}(\Gamma) \cdot \mathcal{V}_{\mathrm{energy}}(\Gamma) \cdot \mathcal{R}_{\mathrm{memory}}(\Gamma), \tag{26}$$

where Γ is a trajectory. The three factors correspond to basin diversity, energetic viability, and memory-based recoverability.

7.1 Basin Diversity

Let the trajectory visit a sequence of configurations $\{s_t\}$. We cluster sampled configurations into basin classes using normalized Hamming distance,

$$d_H(s_a, s_b) = \frac{1}{N}\sum_{i=1}^{N} \mathbf{1}\left[s_i^{(a)} \neq s_i^{(b)}\right]. \tag{27}$$

If p_k is the fraction of sampled states assigned to basin cluster k, basin diversity can be estimated by the entropy

$$\mathcal{D}_{\text{basin}}(\Gamma) = -\sum_k p_k \log p_k. \tag{28}$$

This term is small when the system remains trapped in a single basin and larger when it explores multiple distinguishable basins.

7.2 Energetic Viability

Exploration alone is not sufficient. At high temperature, a spin glass may visit many configurations, but this can amount to incoherent wandering rather than useful exploration. We therefore weight basin diversity by energetic viability. A simple choice is

$$\mathcal{V}_{\text{energy}}(\Gamma) = \exp\left[-\frac{\langle H(s_t)\rangle_\Gamma}{T_v}\right], \tag{29}$$

where T_v is a viability temperature. Equivalently, in numerical experiments one may use a normalized monotonic transformation of $-\langle H\rangle$. The point is that useful exploration should remain constrained by physical compatibility.

7.3 Memory-Based Recoverability

The third component is recoverability. Let s_{settle} denote the low-temperature configuration reached before perturbation. During the recovery phase, define

$$\mathcal{R}_{\text{memory}}(\Gamma) = \frac{1}{T_{\text{rec}}}\sum_{t\in\text{recover}} \frac{1}{N}\sum_i s_i(t) s_i^{\text{settle}}. \tag{30}$$

This term is high when the system can return to, or remain compatible with, a previously sedimented coherent basin. It distinguishes productive exploration from irreversible dispersion.

7.4 Curiosity Window Conjecture

Let μ denote the strength of memory/coherence pressure. The ECF curiosity-window conjecture can then be stated as follows:

> **Curiosity Window Conjecture.** In frustrated systems with sedimented memory, the useful-exploration functional $\mathcal{K}_{\text{ECF}}$ is non-monotonic in coherence pressure. There exists an intermediate value μ^* such that
>
> $$\mathcal{K}_{\text{ECF}}(\mu^*) > \mathcal{K}_{\text{ECF}}(\mu)$$
>
> for both weak-memory and over-constrained regimes.

Equivalently,

$$\frac{d\mathcal{K}_{\mathrm{ECF}}}{d\mu} > 0 \quad \text{for} \quad \mu < \mu^*, \qquad \frac{d\mathcal{K}_{\mathrm{ECF}}}{d\mu} < 0 \quad \text{for} \quad \mu > \mu^*. \tag{31}$$

The interpretation is direct. When μ is too small, the system explores but does not preserve memory. It becomes noisy and weakly recoverable. When μ is too large, the system preserves memory but loses exploratory freedom. It becomes rigid and basin-fixated. At intermediate μ, the system can leave its current basin while retaining enough historical coherence to recover and reintegrate.

7.5 Relation to Criticality and Edge-of-Chaos Ideas

The curiosity window is related to, but not identical with, edge-of-chaos or optimal-noise arguments. Edge-of-chaos claims usually state that computation or adaptation is enhanced near a transition between order and disorder. The ECF claim is narrower and more operational: adaptive exploration requires the simultaneous maximization of basin diversity, energetic viability, and memory-based recoverability. Thus the relevant optimum is not merely a point of high susceptibility or instability, but a regime in which novelty remains coherent.

In this sense, the curiosity window provides a possible bridge between spin-glass physics and cognitive exploration. A cognitive system that never leaves its established basin becomes rigid; a system that loses all basin structure becomes incoherent. Curiosity appears in the intermediate regime where new basins can be sampled without destroying continuity with prior organization.

7.6 Experimental Implication

The most direct experimental test is to scan μ, perturbation temperature, or incoherence penalty and measure $\mathcal{K}_{\mathrm{ECF}}$. The prediction is an inverted-U curve:

$$\mathcal{K}_{\mathrm{ECF}}(\mu) \quad \text{has a maximum at intermediate coherence pressure.} \tag{32}$$

This is stronger than showing that the ECF model has better recovery. It predicts a specific non-monotonic structure: too little coherence gives exploration without integration; too much coherence gives integration without exploration; useful curiosity lies between them.

We also scanned the memory/coherence pressure μ. Too little coherence pressure produces weak memory and relatively unconstrained wandering. Too much coherence pressure can freeze the system into rigid historical replay. Between these extremes, useful exploration can peak. We define a simple useful-exploration score as

$$U = A_{\mathrm{perturb}} \times D_{\mathrm{energy}} \times R_{\mathrm{recover}}, \tag{33}$$

where A_{perturb} is the mean acceptance rate during perturbation, D_{energy} is a crude diversity measure based on visited energy levels, and R_{recover} is recovery quality. This produces a curiosity-window-like curve.

The final spin and memory fields provide a qualitative view of the difference between the baseline and ECF dynamics.

8 Novelty and Positioning

The proposed ECF-spin-glass model should be positioned carefully. Its novelty does not lie in the isolated introduction of a memory variable, nor in the observation that spin glasses display history dependence. Spin-glass theory already contains rich accounts of frustration,

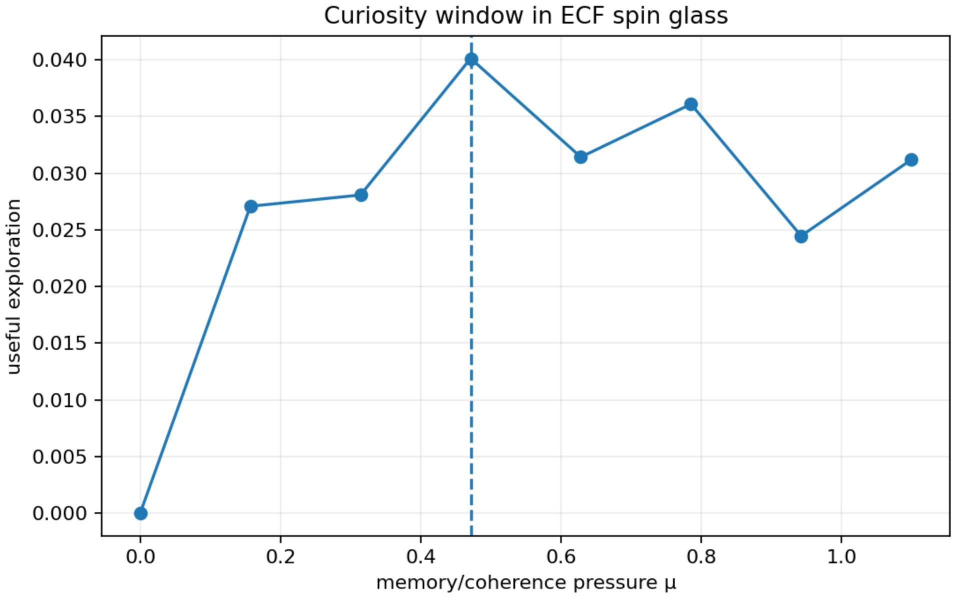

Figure 7: Curiosity-window prediction. Useful exploration, defined as basin diversity times energetic viability times memory-based recoverability, is expected to peak at intermediate coherence pressure.

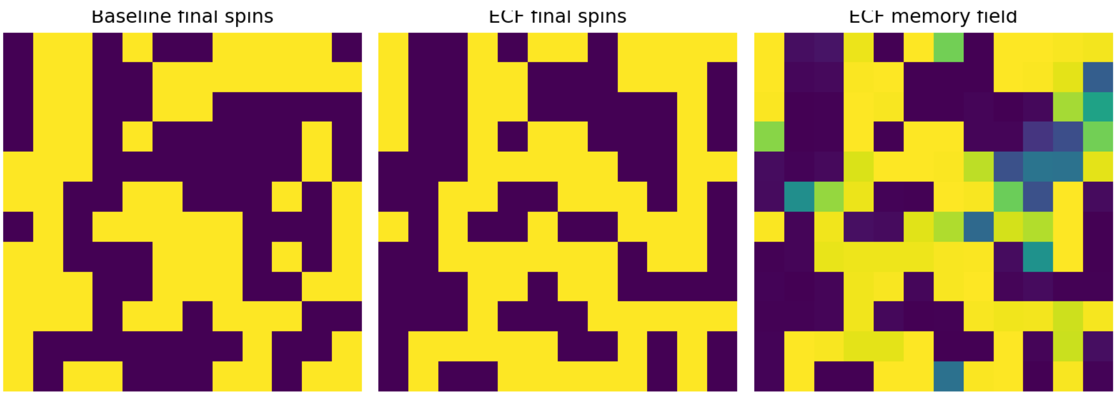

Figure 8: Final spin configurations and ECF memory field.

rugged energy landscapes, metastability, aging, rejuvenation, and memory. Similarly, history-dependent or phenomenological memory terms are not, by themselves, sufficient to define a new theory.

The novelty lies instead in defining coherence as a path-level balance between energy, history, frustration, and reach. In this formulation, the relevant object is not only the instantaneous configuration s_t, but the trajectory

$$\Gamma = \{s_0, s_1, \dots, s_T\}. \tag{34}$$

The ECF interpretation therefore shifts the focus from state evaluation to trajectory evaluation. Ordinary spin-glass dynamics is centered on the Hamiltonian $H(s)$. The ECF extension is centered on a trajectory probability,

$$P(\Gamma) \propto \exp\left[-\mathcal{S}_{\mathrm{ECF}}[\Gamma]\right], \tag{35}$$

where the ECF action includes not only energetic cost, but also memory compatibility, local incoherence, and future accessibility.

A concise statement of the proposed contribution is therefore:

> *Novelty lies not in adding memory, but in defining coherence as a path-level balance between energy, history, frustration, and reach.*

This distinction is important. A critic could reasonably interpret the implemented model as a modified Hamiltonian with a slow memory field. Such a criticism is valid if the model is presented only at the level of the local update rule. However, the intended contribution is broader: the memory term is a local approximation to a trajectory-level principle. The ECF claim is that complex systems should not be evaluated only by their instantaneous energetic optimality, but also by their ability to preserve historically formed structure while retaining access to viable future states.

This leads to the following conceptual contrast:

Classical spin-glass emphasis	**ECF emphasis**
Energy landscape	Coherence landscape
Local and global minima	Recoverable coherent basins
Relaxation and trapping	Trajectory continuity and re-entry
Frustration as constraint conflict	Frustration as local incoherence
Thermal exploration	Coherence-constrained exploration
State probability $P(s)$	Path probability $P(\Gamma)$

The strongest claim is not that the ECF system always finds lower-energy states. Indeed, in preliminary simulations the baseline and ECF systems may reach similar final energies. The more interesting claim is that two systems with similar energy can differ in their recovery, memory alignment, and future accessibility. In this sense, ECF separates energetic optimization from historical coherence.

Formally, this suggests that the Hamiltonian $H(s)$ is insufficient as the sole descriptor of adaptive organization in history-sensitive frustrated systems. Two configurations may satisfy

$$H(s_a) \approx H(s_b), \tag{36}$$

while differing substantially in reach,

$$R(s_a) \gg R(s_b), \tag{37}$$

or in memory compatibility,

$$M(s_a, m_t) \gg M(s_b, m_t). \quad (38)$$

The ECF hypothesis is that these differences matter for perturbation response and recovery. A low-energy state with low reach may be brittle, whereas a state with comparable energy but higher reach may be more adaptable. Likewise, a state compatible with sedimented memory may be more recoverable after perturbation than an energetically similar state with weak historical continuity.

Thus, the proposed contribution should be understood as a phenomenological but testable reframing:

> *Spin-glass memory is not merely a residue of slow relaxation; it can be modeled as sedimented coherence that reshapes future accessibility.*

At the present stage, this is not yet a complete alternative to replica, cavity, or dynamical mean-field approaches. Rather, it is a minimal computational framework for asking a different question: not only which configurations are energetically favorable, but which trajectories preserve coherent organization under perturbation.

The immediate testable prediction is that coherence-based quantities should explain recovery behavior better than energy alone. In particular, one may compare states with similar $H(s)$ but different $C(s, m)$, $R(s)$, or $M(s, m)$, and test whether the latter quantities better predict post-perturbation recovery. If confirmed across system sizes, disorder realizations, and perturbation protocols, this would strengthen the case that ECF provides a nontrivial extension of standard energy-landscape descriptions.

9 Preliminary Numerical Summary

A representative small run gave the following results:

Table 1: Preliminary summary metrics from the ultra-fast demonstration. Values are illustrative, not final statistical estimates.

Mode	Final E/N	Recover E/N	Frustration	Recovery	Acceptance	Coherence
Baseline	-1.361	-1.298	0.176	-0.068	0.378	1.298
ECF	-1.361	-1.334	0.167	0.601	0.265	1.968

The important point is not that the ECF system always reaches lower final energy. In this run, the final energies were nearly identical. The important difference is that the ECF system retained and recovered a historically coherent basin more strongly after perturbation.

10 Discussion

These experiments suggest a possible way to formalize ECF in physics without abandoning established spin-glass theory. The Hamiltonian remains central. However, the state-transition rule is enriched by a slowly sedimented memory field and an incoherence-sensitive term.

This allows spin-glass dynamics to be interpreted not only as relaxation on a rugged landscape but also as a process of trajectory coherence. Aging and memory effects then become less mysterious: the system is not merely moving through configuration space; it is progressively altering the effective landscape through its own history.

The ECF view may be especially useful for complex systems in which equilibrium concepts are insufficient. Biological cognition, neural dynamics, social systems, adaptive materials, and learning systems often do not simply minimize an externally given energy. They develop internal histories that shape future accessibility. In this sense, the ECF-augmented spin glass can serve as a minimal model of history-sensitive complex organization.

11 Limitations

The present experiment is intentionally minimal. Several limitations must be addressed before making strong physical claims:

1. The lattice size is small in the ultra-fast demonstration.
2. The ECF coherence functional is heuristic.
3. The memory field is local and simple.
4. No finite-size scaling analysis was performed.
5. No comparison was made against more sophisticated algorithms such as parallel tempering.
6. The curiosity-window score is illustrative and should be replaced by more principled information-theoretic or dynamical measures.

12 Future Work

Future work should test larger systems, multiple disorder realizations, and statistically robust ensembles. Natural extensions include:

1. finite-size scaling of ECF recovery effects;
2. temperature-cycling experiments resembling spin-glass rejuvenation and memory protocols;
3. comparison with parallel tempering and cluster methods;
4. nonlocal or graph-based memory fields;
5. connection between ECF coherence and overlap distributions;
6. application to Hopfield networks, reservoir systems, and optimization landscapes;
7. formulation of an ECF dynamical mean-field theory.

13 Conclusion

We proposed and implemented a minimal ECF-inspired extension of spin-glass dynamics. The central idea is to augment ordinary energy-based dynamics with sedimented memory and incoherence sensitivity. Preliminary simulations show that this can produce stronger recovery after perturbation and a curiosity-window-like dependence on coherence pressure. The broader implication is that ECF may provide a useful language for complex physical systems in which history, memory, and trajectory coherence are not secondary effects but organizing principles.

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