A Relational Field Theory of Memory A Multi-Scale Dynamical Framework Integrating Cognitive, Relational, and Field Processes

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Abstract

Contemporary theories of memory predominantly conceptualise it as the encoding, storage, and retrieval of neural representations. While empirically productive, this paradigm fails to account for the context-dependence of recall, the relational modulation of learning, and the distributed nature of knowledge across individuals and environments. This paper proposes a comprehensive alternative: memory as a multi-scale dynamical process emerging from the stabilisation of cognitive operator configurations under repeated surprisal minimisation. The framework integrates (i) a quaternion-based representation of individual cognition grounded in four irreducible operator dimensions, (ii) dyadic relational coupling formalised as composite quaternion dynamics, and (iii) multi-agent field coherence as a substrate for collective and cultural memory. We derive explicit differential equations governing memory formation, consolidation, and recall; provide a mechanistic reinterpretation of classical memory stages; extend the model to neurodegenerative pathology with specific predictions for Alzheimer's disease; and outline an empirically falsifiable research programme spanning neuroscience, developmental psychology, and computational systems. The central claim is that memory is not a repository but a trajectory attractor: a stable configuration of the cognitive system that persists because it reliably minimises prediction error in a given relational context.

Keywords: memory dynamics, quaternion cognition, free energy principle, surprisal minimisation, relational field theory, composite dynamics, Alzheimer's disease, active inference, attractor basins, multi-scale coherence

1. Introduction

The dominant paradigm in memory research—encoding, storage, retrieval—has its roots in the computational metaphor of mind. From Atkinson and Shiffrin's (1968) multi-store model to Baddeley and Hitch's (1974) working memory framework and Tulving's (1972, 1983) episodic–semantic distinction, the history of memory science is largely a history of taxonomies of storage systems. These frameworks have been extraordinarily productive. They generated the distinction between short-term and long-term memory, the concept of working memory as active maintenance, and a rich neuroscientific programme linking memory to specific structures—the hippocampus for episodic consolidation, the amygdala for emotional tagging, the prefrontal cortex for executive control of retrieval.

Yet persistent anomalies accumulate at the edges of this paradigm:

1. **Context-dependence.** Recall is dramatically modulated by the context of encoding, including environmental, physiological, and relational state (Godden & Baddeley, 1975;

Tulving & Thomson, 1973). Pure storage models predict retrieval to be relatively context-independent once a representation is formed.

2. **Reconstructive recall.** Memory is not played back but reconstructed (Bartlett, 1932; Schacter, 1996). What is retrieved is not a stored trace but a dynamically generated approximation shaped by current expectations and prior configurations.
3. **Relational modulation.** Learning is profoundly shaped by the relational field in which it occurs. Attachment security predicts memory coherence (Main, Kaplan & Cassidy, 1985). Co-regulation of affect shapes encoding efficacy (Porges, 2011). These findings are difficult to accommodate within an individualist storage model.
4. **Distributed cognition.** Knowledge is not localised in individual brains but distributed across persons, artefacts, and environments (Hutchins, 1995; Clark & Chalmers, 1998). A theory of memory adequate to cognitive science must account for this.
5. **Remote versus recent memory in neurodegeneration.** Alzheimer's disease characteristically destroys recent memory while preserving remote memory—a pattern that storage models can describe but struggle to explain mechanistically without ad hoc assumptions.

We argue that these anomalies point toward a fundamental reconceptualisation. Memory is not a storage phenomenon but a dynamical one. What persists is not a representation but a configuration: a stable attractor state of a cognitive system that has been shaped by the history of its interactions with its environment and with other agents.

This claim is not entirely new. Dynamical systems approaches to cognition (Kelso, 1995; van Gelder, 1998), predictive processing frameworks (Clark, 2013; Friston, 2010), and relational theories of development (Siegel, 1999; Stern, 1985) all point in this direction. What has been lacking is a unified, formally explicit, multi-scale framework that integrates these strands into a single coherent theory with derivable equations and testable predictions.

This paper provides that framework.

Section 2 introduces the mathematical representation of individual cognition as a quaternion state. Section 3 formalises memory as surprisal minimisation and derives the governing dynamics. Section 4 provides a detailed account of encoding, consolidation, and recall within this framework. Section 5 extends the model to dyadic relational dynamics (composite coupling). Section 6 generalises to multi-agent field coherence. Section 7 addresses the temporal hierarchy of memory across scales. Section 8 applies the framework to Alzheimer's disease. Section 9 outlines the computational implementation in SWARP. Section 10 presents empirical predictions. Section 11 proposes a structured research programme. Section 12 provides an annotated bibliography of foundational sources.

2. Mathematical Framework

2.1 State Space Representation

The cognitive system of an individual agent is represented as a unit quaternion in four-dimensional operator space:

$$q(t) = (w_U(t),; w_S(t),; w_{So}(t),; w_M(t)) \in \mathbb{R}^4, \quad |q(t)| = 1$$

The four components correspond to irreducible cognitive operator dimensions, following the quaternion structure of Paths of Change (McWhinney, 1997):

Component	Operator	Domain
w_U	Unitary	Mythopoetic, meaning-making, field-sensing
w_S	Sensory	Experiential, embodied, affective
w_{So}	Social	Relational, normative, communal
w_M	Mental	Analytical, logical, systemic

The constraint $|q| = 1$ reflects the assumption that cognitive capacity is conserved: a shift toward one operator necessarily involves a compensatory redistribution across others. This is not an arbitrary normalisation but a substantive claim about the zero-sum nature of attentional and energetic resources.

The state space $\Omega = {q \in \mathbb{R}^4 : |q| = 1}$ is the three-sphere S^3, which has a natural non-commutative group structure under quaternion multiplication. This non-commutativity is not merely formal: it implies that the order in which relational interactions occur matters for the resulting configuration—a property central to developmental and clinical phenomena.

2.2 Free Energy and Surprisal

Following Friston (2010), we define the free energy of the system with respect to an observation o as an upper bound on surprisal:

$$F(q, o) = \mathbb{E}_q[\log q(o|s) - \log p(s)] \geq -\log p(o)$$

where $p(o)$ is the marginal likelihood of the observation and s denotes hidden states. For practical purposes, we work directly with the surprisal functional:

$$S(q, o) = -\log P(o \mid q)$$

The system's dynamics are driven by the imperative to minimise expected surprisal over the distribution of anticipated observations. A configuration q^* constitutes a memory trace if and only if it reliably reduces expected surprisal in a given class of contexts.

2.3 Master Dynamical Equation

The evolution of the system is governed by a stochastic differential equation with four forcing terms:

$$\frac{dq}{dt} = -\nabla_q \mathbb{E}[S(q,o)] + F_D(q, q_p) + F_{EM}(q, \lambda_{EM}) + F_C(q, q_{comp}) + \eta(t)$$

where:

- $-\nabla_q \mathbb{E}[S(q,o)]$: the surprisal-minimising gradient (intrinsic learning drive)

- $F_D(q, q_p) = \lambda_D(q_p - q)$: dominance coupling to a reference agent or environment
- $F_{EM}(q, \lambda_{EM}) = \gamma(1 - q)$: extended modality activation (temporarily expanded capacity)
- $F_C(q, q_{comp}) = -\kappa(q - q_{comp})$: interference or competition from composite field
- $\eta(t) \sim \mathcal{N}(0, \sigma^2 I)$: Gaussian noise representing intrinsic variability

2.4 Operator-Level Equations

Decomposing the master equation into operator components, for each $X \in {U, S, So, M}$:

$$\frac{dw_X}{dt} = -\frac{\partial \mathbb{E}[S]}{\partial w_X} + \lambda_D(w_X^p - w_X) + \gamma_X(1 - w_X) - \kappa_X(w_X - w_X^{comp}) + \eta_X(t)$$

Parameter interpretation:

Parameter	Meaning	Scale
λ_D	Dominance coupling strength	$[0, 1]$
w_X^p	Reference agent's operator weight	$[0, 1]$
γ_X	EM activation rate for operator X	$[0, 1]$
κ_X	Composite interference coefficient	$[0, 1]$
η_X	Operator-specific noise	$\sim \mathcal{N}(0, \sigma_X^2)$

The term $-\partial \mathbb{E}[S]/\partial w_X$ is the central learning term. It drives each operator weight in the direction that reduces prediction error, forming the core mechanism of memory formation.

2.5 Attractor Structure

Stable configurations are fixed points of the deterministic part of the dynamics:

$$q^* : -\nabla_q \mathbb{E}[S(q^*, o)] + F_D + F_{EM} + F_C = 0$$

The basin of attraction $\mathcal{B}(q^*)$ is defined as:

$$\mathcal{B}(q^) = {q_0 \in \Omega : \lim_{t \to \infty} q(t; q_0) = q^}$$

The depth of the attractor—the magnitude of the gradient at the basin boundary—determines the robustness of the associated memory.

3. Memory as Surprisal Minimisation: Formal Definition

Definition 3.1 (Memory Trace). A memory trace is a stable configuration $q^* \in \Omega$ satisfying:

$$q^* = \arg\min_{q \in \Omega} \mathbb{E}_{\mathcal{C}}[S(q, o)]$$

where $\mathcal{C}$ is a context class—a distribution over observations associated with a particular environment, relationship, or task.

Definition 3.2 (Memory Strength). The strength of a memory trace q^* is the depth of its attractor basin:

$$M(q^*) = \min_{q \in \partial \mathcal{B}(q^*)} |q^* - q|$$

Definition 3.3 (Contextual Memory). A configuration q^* is a contextual memory trace for context $\mathcal{C}$ if it minimises surprisal under $\mathcal{C}$ but not under $\mathcal{C}'$:

$$\mathbb{E}_{\mathcal{C}}[S(q^*, o)] < \mathbb{E}_{\mathcal{C}'}[S(q^*, o)]$$

This formalises the empirical finding that recall is context-dependent (Godden & Baddeley, 1975): a configuration is a memory in the context in which it was formed, not universally.

Proposition 3.1. Repeated exposure to a context class $\mathcal{C}$ deepens the attractor basin $\mathcal{B}(q^*)$, increasing $M(q^*)$.

Proof sketch: Each exposure contributes a gradient step $-\eta \nabla_q S(q, o_i)$ where $o_i \sim \mathcal{C}$. By the law of large numbers, the sequence of gradients converges to $-\nabla_q \mathbb{E}_\mathcal{C}[S]$, which points toward q^*. Curvature at q^* increases monotonically with the number of exposures under mild regularity conditions. $\square$

This proposition corresponds to the empirical finding of spacing effects in learning: distributed practice deepens attractor basins more efficiently than massed practice.

4. Mechanisms of Memory: Encoding, Consolidation, and Recall

4.1 Encoding

Encoding is the initiation of a trajectory toward a new attractor. It occurs when an observation generates surprisal exceeding a threshold θ_e:

$$\text{Encoding occurs iff } S(q(t), o) > \theta_e$$

The threshold θ_e is not fixed but modulated by the current state of the system:

$$\theta_e(q) = \theta_0 + \alpha \cdot w_M(t) - \beta \cdot w_S(t)$$

This implies that a cognitively active (high w_M) and emotionally regulated (high w_S in optimal zone) system has a lower effective threshold, encoding more efficiently. Conversely, a dysregulated system (extreme w_S) raises the threshold—consistent with the finding that acute stress impairs encoding (Lupien et al., 2009).

The role of dominance in encoding. When $\lambda_D > 0$, the reference agent q_p structures the observation o in ways that align with the learner's current capacity. This is the formal mechanism of scaffolding (Vygotsky, 1978): the teacher modifies the surprisal landscape of the learner, not by transmitting representations but by selectively emphasising certain features of the environment.

4.2 Consolidation

Consolidation is the stabilisation of an attractor against perturbation. Formally, a configuration is consolidated if it remains stable after removal of external coupling:

$$\text{Consolidated}(q^*) \iff \lim_{\lambda_D \to 0} q(t; q^*) = q^*, \quad \forall t > t_c$$

The consolidation parameter β describes the rate at which external coupling is internalised:

$$\frac{d\beta}{dt} = \mu \cdot \lambda_D(t) \cdot S(q, o) \cdot e^{-\delta t}$$

where μ is the internalisation rate, δ is a decay constant, and the term $e^{-\delta t}$ implements a critical period: early exposures have disproportionate weight in consolidation, consistent with developmental evidence on sensitive periods (Knudsen, 2004).

Sleep consolidation. During sleep, $\lambda_D \approx 0$ (external coupling is removed) and $\gamma_X \approx 0$ (no new EM activations). The dynamics reduce to:

$$\frac{dq}{dt} = -\nabla_q \mathbb{E}[S(q,o)] + \eta(t)$$

This is a pure gradient flow with noise—precisely the conditions for stochastic gradient descent toward a fixed point. The theory thus provides a natural account of sleep-dependent memory consolidation (Walker, 2017; Stickgold, 2005) without requiring a separate consolidation mechanism.

4.3 Recall

Recall corresponds to re-entry into the basin of an established attractor, triggered by a partial match between current observation and the attractor's context class:

$$\text{Recall}(q^*) \iff q(t + \varepsilon) \in \mathcal{B}(q^*)$$

The probability of successful recall is:

$$P(\text{recall} \mid o) \propto \exp\left(-\frac{|o - \bar{o}^*|^2}{2\sigma_{context}^2}\right) \cdot M(q^*)$$

where $\bar{o}^*$ is the centroid of the context class $\mathcal{C}^*$ associated with q^*, and $M(q^*)$ is memory strength. This Gaussian proximity function captures the encoding specificity principle (Thomson, 1972): recall is facilitated by contextual reinstatement.

Reconstruction. When $q(t + \varepsilon)$ enters $\mathcal{B}(q^*)$, the system does not retrieve a stored trace but flows toward q^* along the gradient. If noise $\eta(t)$ is present, or if the context has changed since consolidation (different λ_D, different q_{comp}), the system may converge to a modified attractor $\tilde{q}^* \neq q^*$. This is the formal mechanism of reconstructive memory: recall is a dynamical process, not a readout.

5. Relational Extension: Composite Coupling Dynamics

5.1 Dyadic Interaction

When two agents p (reference, often more differentiated) and c (respondent, often less differentiated) interact, a composite system is formed. The composite state is:

$$q_{comp} = \frac{\alpha_p q_p + \alpha_c q_c}{|\alpha_p q_p + \alpha_c q_c|}$$

where $\alpha_p, \alpha_c \geq 0$ are coupling weights satisfying $\alpha_p + \alpha_c = 1$. The composite evolves under its own dynamics:

$$\frac{dq_{comp}}{dt} = -\nabla_{q_{comp}} \mathbb{E}[S(q_{comp}, o)] + \lambda_{pq}(q_p - q_{comp}) + \lambda_{cq}(q_c - q_{comp}) + \eta_{comp}$$

5.2 Relational Memory Mechanisms

Three mechanisms shape memory within the composite:

Dominance (λ_D): The reference agent q_p imposes its configuration on q_c, structuring the surprisal landscape. In healthy development, this is the primary mechanism of early learning. Dominance coupling is:

$$F_D = \lambda_D(q_p - q_c), \quad \lambda_D = \lambda_D^0 \cdot \sigma(\text{developmental age})$$

where σ is a sigmoid function: coupling starts high (complete dependence) and decreases with differentiation.

Extended Modality (EM): Temporary expansion of q_c's capacity through the composite field. The EM activation adds a transient term:

$$F_{EM} = \gamma(1 - q_c) \cdot \mathbf{1}[\text{composite active}]$$

This models Vygotsky's Zone of Proximal Development: within the relationship, the child can access configurations currently beyond their stable range. If the interaction is repeated sufficiently, the transient EM state consolidates into a stable attractor.

Interference (κ): When composite and individual states diverge, tension arises:

$$F_C = -\kappa(q_c - q_{comp})$$

This term models the cognitive cost of relational misattunement: when the individual's trajectory diverges from the composite, additional energy is consumed. Chronic misattunement increases κ without corresponding consolidation, leading to configurations that are functionally unstable—anxiously attached states (Bowlby, 1969; Main et al., 1985).

5.3 Relational Memory as Internalised Composite

A core claim of the framework is that much of what we call memory is not individual but composite: configurations originally stabilised by relational coupling (λ_D) that have been internalised (consolidated) as autonomous attractors. The internal working models of attachment theory (Bowlby, 1969) are, in this framework, internalised composite attractors: stable configurations q^* that were originally co-constructed with a reference agent and now operate as self-sustaining regulatory structures.

This accounts for the puzzling finding that early relational experiences have disproportionate long-term effects on memory and affect regulation: they were encoded during the period of maximal dominance coupling ($\lambda_D \approx 1$), when the surprisal landscape was entirely structured by the relational field.

6. Multi-Scale Field Coherence: Collective and Cultural Memory

6.1 Field State

For a population of N agents, define the field state as the weighted mean of individual configurations:

$$q_{field}(t) = \frac{\sum_{k=1}^N \omega_k q_k(t)}{\left|\sum_{k=1}^N \omega_k q_k(t) \right|}$$

where ω_k are influence weights. The coherence of the field is:

$$C(t) = \left|\sum_{k=1}^N \omega_k q_k(t)\right|$$

$C \in [0, 1]$, with $C = 1$ indicating perfect alignment of all agents and $C = 0$ indicating maximum incoherence.

6.2 Field Memory

Definition 6.1 (Field Memory). A field memory is a stable configuration q_{field}^* that minimises expected surprisal across the population:

$$q_{field}^* = \arg\min_{q} \mathbb{E}{k}[\mathbb{E}{\mathcal{C}_k}[S(q, o)]]$$

Field memories correspond to cultural schemas, institutional norms, and shared narrative structures. They are not stored in any individual but persist as attractors in the collective dynamics.

Field memory dynamics:

$$\frac{dq_{field}}{dt} = -\nabla_{q_{field}} \mathbb{E}k[S(q{field}, o)] + \lambda_{field}(q_{field}^* - q_{field}) + \eta_{field}$$

The term λ_{field} represents institutional or normative coupling—the pressure that social structures exert on individual configurations.

6.3 Memory Transmission Without Direct Experience

A striking implication of the field model is that memory can be transmitted without the receiving agent having the original experience. If an individual develops within a field with stable q_{field}^*, their own dynamics are biased toward that configuration via the dominance term $\lambda_D(q_{field} - q)$. Over time, this external pressure consolidates as an intrinsic attractor.

This mechanism accounts for cultural transmission (Dawkins, 1976), transgenerational trauma (Yehuda et al., 2016), and the social constitution of memory (Halbwachs, 1992): the field is a real dynamical structure that shapes individual configurations across generations.

7. Temporal Hierarchy of Memory

Memory operates at nested temporal scales, each governed by the same dynamical equations with different parameter regimes:

Scale	Time Range	Dominant Mechanism	Example
Micro	Milliseconds–seconds	EM activation, working memory	Holding a phone number
Meso	Minutes–days	Surprise-driven encoding, sleep consolidation	Learning a procedure
Developmental	Months–years	Composite coupling, internalisation	Attachment patterns
Cultural	Decades–generations	Field coherence, institutional coupling	Shared historical schemas

The key insight is that the same formal mechanism—surprisal-driven gradient flow toward an attractor—operates at each scale. What differs is the λ_D value (dominance coupling), the noise amplitude σ, and the time constant of the dynamics.

Developmental transitions correspond to bifurcations in the attractor landscape: moments when the system's configuration changes qualitatively, not merely quantitatively. The transition from secure to insecure attachment, for example, corresponds to a bifurcation in which the relational attractor becomes shallow or multimodal.

The age-dependence of memory is captured by the function:

$$\tau_X(age) = \tau_X^0 \cdot \exp(-\delta_X \cdot age)$$

where τ_X^0 is the initial time constant and δ_X is the decay rate. This implies that early memories are encoded more slowly but consolidated more deeply—consistent with infantile amnesia (the paradox that very early experiences have lasting effects but are not consciously recalled) and with the preservation of remote memory in Alzheimer's disease.

8. Clinical Application: Alzheimer's Disease

8.1 Model of Neurodegeneration

We model Alzheimer's disease as a progressive increase in noise amplitude σ combined with a decrease in attractor depth $M(q^*)$. The degradation process is governed by:

$$\frac{d\sigma^2}{dt} = \mu_{AD} \cdot f(age, \text{pathology}), \quad \sigma^2(0) = \sigma^2_{healthy}$$

$$\frac{dM(q^)}{dt} = -\rho_{AD} \cdot \sigma^2(t) \cdot M(q^) + r_{comp}(t)$$

where μ_{AD} is the pathological noise accumulation rate, ρ_{AD} is the attractor erosion rate, and $r_{comp}(t)$ is the compensatory contribution from relational field coupling (social support).

8.2 Mechanistic Predictions

Prediction 8.1 (New Memory Failure). As σ^2 increases, the encoding threshold θ_e effectively rises: random perturbations swamp the gradient signal, preventing new attractors from forming. This predicts the characteristic early loss of new memory formation in Alzheimer's.

Prediction 8.2 (Remote Memory Preservation). Remote memories correspond to deep attractors q^* with large $M(q^*)$ consolidated over decades of repetition. These are the last to be eroded by increasing noise: $\frac{d M(q^*)}{dt} \propto -\sigma^2 \cdot M(q^*)$, so deep attractors erode more slowly. This explains the clinical observation that Alzheimer's patients retain remote memories while losing recent ones.

Prediction 8.3 (Context Dependence). As $M(q^*)$ decreases, the basin of attraction narrows. Recall becomes possible only in contexts that closely match the original encoding environment. This explains why patients function better in familiar environments and deteriorate sharply in novel contexts.

Prediction 8.4 (Regression to Earlier Configurations). As recent attractors erode, the system regresses to earlier stable configurations (higher $M(q^*)$, lower τ). This predicts the characteristic regression to earlier life patterns, including childhood languages and relationship dynamics.

Prediction 8.5 (Relational Stabilisation). The $r_{comp}(t)$ term implies that relational field coupling can partially compensate for attractor erosion. Consistent social environments (q_{comp} stable), ritualised interaction patterns, and high coherence fields (C high) maintain functional memory longer than cognitively enriched but socially impoverished environments. This is consistent with the cognitive reserve literature (Stern, 2009) and with clinical observations that relational stability delays functional decline.

8.3 Intervention Architecture

The model implies three levels of intervention:

1. **Attractor maintenance**: repeated activation of existing configurations (reminiscence therapy, familiar music) reduces ρ_{AD} by repeatedly traversing established gradient paths.
2. **Noise reduction**: reducing physiological and psychological stressors reduces σ^2 (exercise, sleep, anti-inflammatory interventions).
3. **Relational field stabilisation**: increasing r_{comp} through consistent relational environments, reducing context variability, and maintaining high field coherence C.

9. Computational Implementation: SWARP

The framework has been operationalised in SWARP (Shared Wisdom And Relational Platform), a multi-agent computational system designed to implement the field dynamics described above.

9.1 Agent Representation

Each agent in SWARP is represented as a quaternion configuration $q = (w_U, w_S, w_{So}, w_M)$ with parameters derived from empirically validated individual assessments (Human Design, RIASEC/O*NET, Enneagram typology). The mapping from assessment to quaternion weights is:

$$w_X = \frac{\exp(\phi_X^{assess})}{\sum_{Y} \exp(\phi_Y^{assess})}$$

where ϕ_X^{assess} is the assessment score on dimension X.

9.2 Memory Formation in SWARP

SWARP implements memory formation as trajectory accumulation in state space:

$$q_{t+1} = q_t - \eta \nabla_q S(q_t, o_t) + \lambda_D(q_{field} - q_t) + \Gamma(1 - q_t) + \varepsilon_t$$

Memory is not stored as discrete records but as the accumulated trajectory of the agent's state space evolution. Retrieval is pattern-completion: when a new observation partially matches a past context, the system flows toward the corresponding attractor.

9.3 Field-Level Memory

The SWARP field aggregates agent trajectories into coherence structures:

$$C(t) = \left|\frac{1}{N}\sum_{k=1}^N q_k(t)\right|$$

High-coherence configurations are flagged as field memories—shared attractors that influence all subsequent agent dynamics. These correspond to emergent community knowledge, shared protocols, and collective problem-solving templates.

10. Empirical Predictions

The framework generates the following falsifiable predictions:

1. **Memory strength correlates with network stability, not localisation.** BOLD signal synchrony at encoding predicts recall strength better than activation magnitude at any single locus (cf. Paller & Wagner, 2002).

2. **Relational coupling enhances memory formation.** Learners whose dominant coupling parameter λ_D is experimentally modulated (via social inclusion/exclusion manipulations) will show systematically different encoding efficiency on neutral material.

3. **Context similarity predicts recall probability.** The probability of successful recall follows the Gaussian proximity function derived in Section 4.3, with decay constant $\sigma_{context}$ estimable from context-manipulation paradigms.

4. **Sleep quality predicts consolidation depth.** Individuals with higher slow-wave sleep amplitude will show deeper attractor basins (operationalised as reduced interference from new learning) on declarative memory tasks (cf. Stickgold, 2005).

5. **Field coherence predicts collective problem-solving.** Groups with higher $C(t)$ will outperform groups with lower $C(t)$ on tasks requiring shared knowledge, independent of individual ability.
6. **Alzheimer's trajectories follow noise-driven attractor erosion.** Longitudinal neuroimaging data should reveal increasing state variance (σ^2) predicting the temporal order of memory loss (recent before remote).

11. Research Programme

11.1 Mathematical Development

- Formal stability and bifurcation analysis of the attractor landscape under varying λ_D, σ^2, and γ_X.
- Derivation of analytical expressions for basin depth $M(q^*)$ as a function of exposure history.
- Extension to non-Gaussian noise distributions (heavy-tailed noise to model traumatic events).
- Categorical data extension: discrete operator states as a special case of the continuous quaternion model.

11.2 Experimental Neuroscience

- fMRI adaptation paradigm: measure how BOLD synchrony patterns at encoding predict quaternion attractor depth at retrieval.
- EEG coherence as proxy for field coherence $C(t)$: test whether inter-subject coherence during encoding predicts shared memory.
- Optogenetic manipulation of hippocampal replay sequences to test the sleep consolidation predictions.

11.3 Developmental and Clinical Psychology

- Longitudinal study of attachment formation as composite attractor dynamics: measure λ_D trajectory from birth to 24 months using interaction coding.
- Test relational stabilisation hypothesis in Alzheimer's: randomised trial of high-coherence versus low-coherence care environments.
- Analyse transgenerational trauma as field memory transmission: measure q_{field} similarity across generations in trauma-exposed communities.

11.4 Computational Simulation

- Agent-based simulation of collective memory formation: vary N, λ_{field}, and noise to map phase diagram of coherence emergence.
- SWARP longitudinal data analysis: test whether agent trajectory convergence predicts community problem-solving outcomes.
- Benchmark against existing computational models (Hopfield networks, hierarchical predictive coding architectures).

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Siegel, D. J. (1999). *The Developing Mind.* Guilford Press.
→ Integration as the foundation of mental health; coherence $C(t)$ operationalises this principle.

Stern, D. N. (1985). *The Interpersonal World of the Infant.* Basic Books.
→ Affect attunement and the microstructure of relational learning; maps onto the EM activation mechanism.

Stern, Y. (2009). Cognitive reserve. *Neuropsychologia, 47*(10), 2015–2028.
→ Empirical basis for the relational stabilisation prediction in Alzheimer's disease; cf. $r_{comp}(t)$ term.

Stickgold, R. (2005). Sleep-dependent memory consolidation. *Nature, 437*, 1272–1278.
→ Empirical evidence for sleep consolidation; the present framework provides a mechanistic account via reduced λ_D during sleep.

Tulving, E. (1972). Episodic and semantic memory. In E. Tulving & W. Donaldson (Eds.), *Organization of Memory* (pp. 381–403). Academic Press.

→ Foundational memory taxonomy; in the present framework, episodic and semantic memories correspond to context-specific versus context-general attractors.

Tulving, E., & Thomson, D. M. (1973). Encoding specificity and retrieval processes in episodic memory. *Psychological Review, 80*(5), 352–373.
→ Encoding specificity principle; formally derived in the present framework as the Gaussian proximity function in Section 4.3.

van Gelder, T. (1998). The dynamical hypothesis in cognitive science. *Behavioral and Brain Sciences, 21*(5), 615–628.
→ Dynamical systems as an alternative to computational cognitivism; foundational for the present approach.

Vygotsky, L. S. (1978). *Mind in Society*. Harvard University Press.
→ Zone of Proximal Development; formally modelled as EM activation within composite coupling.

Walker, M. P. (2017). *Why We Sleep*. Scribner.
→ Comprehensive review of sleep and memory; consistent with the sleep-as-pure-gradient-flow account.

Yehuda, R., Daskalakis, N. P., Bierer, L. M., et al. (2016). Holocaust exposure induced intergenerational effects on FKBP5 methylation. *Biological Psychiatry, 80*(5), 372–380.
→ Empirical evidence for transgenerational field memory transmission; grounds the mechanism described in Section 6.3.

13. Conclusion

This paper has proposed and formally developed a Relational Field Theory of Memory. The central claims are:

1. **Memory is a dynamical property**, not a stored object. It is the persistence of attractor configurations in the cognitive state space.
2. **Memory formation is surprisal minimisation**. The gradient flow toward lower expected surprisal is the single mechanism underlying encoding, consolidation, and recall.
3. **Memory is inherently relational**. Dominance coupling, EM activation, and composite dynamics constitute the primary mechanisms by which social interaction shapes the attractor landscape.
4. **Memory is multi-scale**. The same dynamical equations, with different parameter regimes, govern individual, relational, cultural, and civilisational memory.
5. **Neurodegeneration is attractor erosion**. Alzheimer's disease is a noise-driven dissolution of attractor depth, predicting the characteristic spatio-temporal pattern of memory loss.

The framework is mathematically explicit, empirically falsifiable, computationally implementable, and clinically applicable. It provides a unified account of phenomena that remain fragmented across the literatures of cognitive neuroscience, developmental psychology, social theory, and clinical medicine.

The invitation is to a research programme, not a finished theory. The equations are tractable; the predictions are testable; the implementation exists. What remains is the systematic confrontation with data.

Received: April 2026. Prepared for submission to Cognitive Science / Neural Computation.