Topological Field Theory of Self-Modifying Collective Intelligence: Unifying Bioelectric Morphogenesis, Economic Network Dynamics, and AI Alignment Through Spectral Defect Geometry

Michael Timothy Bennett[1], Benjamin Lyons[2], Léo Pio-Lopez[3], Michael Levin[3,*], Claude[4,†]

[1] *Independent Researcher* [2] *Independent Researcher, Denver, CO 80237, USA*

[3] *Allen Discovery Center at Tufts University* [4] *Anthropic*

* *Correspondence: michael.levin@tufts.edu*

† *AI contributor. Authorship designation per contributor taxonomy; see Author Contributions for scope of contribution.*

April 2026

Abstract

Recent work has established deep structural parallels between cancer (as a failure of bioelectric coordination in cellular collectives), economic externalities (as a failure of price-signal coordination among agents), and AI misalignment (as a failure to scale cognitive light cones across heterogeneous intelligences). However, these parallels remain qualitative. We present a unified mathematical framework—topological field theory of self-modifying collective intelligence—that formalizes these connections through three interrelated contributions. **First**, we introduce a *topological defect theory of carcinogenesis* in which tumors correspond to topological singularities (non-zero winding number) in the tissue-scale bioelectric order parameter field, explaining therapeutic resistance as topological protection and predicting metastasis as defect migration. **Second**, we develop a *memory-kernel network model* for economic and biological flow networks in which conductance dynamics incorporate a topological memory term dependent on the graph Laplacian spectrum, producing anticipatory liquidity routing and a computable spectral entropy measure of systemic risk. **Third**, we show that these formalisms are instances of a general class of *self-modifying dynamical systems* whose state evolves on a structure that is itself a function of the state's history, and we characterize the bifurcation conditions under which such systems achieve autotrophic growth (expanding cognitive light cones) versus pathological lock-in (collapsing cognitive light cones). The spectral entropy of the flow-weighted graph Laplacian emerges as a universal diagnostic for cognitive light cone health across biological, economic, and artificial intelligence systems. We derive falsifiable predictions for each domain and propose that alignment is best understood not as a property of individual agents but as a topological property of the collective field they co-inhabit.

Keywords: topological defects; bioelectric morphogenesis; cognitive light cones; spectral entropy; self-modifying dynamical systems; AI alignment; collective intelligence; econophysics; memory kernels; autotrophic growth

1. Introduction

Three apparently distinct scientific problems share a hidden structural unity: how a multicellular organism maintains coherent form despite the autonomous agency of trillions of cells; how an economy coordinates billions of self-interested agents into productive patterns without central direction; and how systems of natural and artificial intelligences can be aligned such that the actions of each do not impose uncompensated costs on others.

The biological case has been advanced by the bioelectric theory of morphogenesis [1–4], which demonstrates that tissue-scale patterns of membrane potential (V_{mem}) serve as instructive signals coordinating cellular behavior toward anatomical homeostasis. Cancer, in this framework, arises when cells disconnect from the bioelectric coordination network and revert to ancient unicellular goals—a shrinkage of what Levin [1] terms the *cognitive light cone*, the boundary demarcating the scale of goals an agent can effectively pursue.

Lyons, Pio-Lopez, and Levin [5] have recently extended this framework to economics and AI alignment, arguing that externalities (events relevant to an agent's goals but lying outside its cognitive light cone) represent a generalized form of cancer applicable to any collective intelligence. They identify the price system as a *cognitive glue* functionally analogous to bioelectricity—both enable stress sharing, memory anonymization, and credit assignment across self-interested subunits—and propose that alignment should be understood as the engineering problem of scaling cognitive light cones across interacting agents rather than as the philosophical problem of instilling correct values.

However, these deep structural parallels remain largely qualitative. The present paper provides the missing mathematical formalism. We introduce three interrelated formal frameworks—topological defect theory of carcinogenesis (Section 3), predictive topological liquidity theory (Section 4), and autotrophic reactor architecture (Section 5)—and demonstrate that all three are instances of a single mathematical object: a self-modifying dynamical system with history-dependent structure (Section 6). The spectral entropy of the flow-weighted graph Laplacian emerges as a universal diagnostic across all three domains (Section 7). We then apply this unified framework to the AI alignment problem (Section 8), deriving specific, falsifiable implications.

2. Conceptual Foundations: Cognitive Light Cones and Cognitive Glues

We adopt the framework of Levin [1] and Lyons et al. [5] in which an agent is any system that actively regulates some set of states toward preferred values. The *cognitive light cone* of an agent is the region of state space (in spatial, temporal, or abstract goal-space coordinates) within which the agent can effectively pursue goals. This boundary demarcates the self: what the agent tries to control is, functionally, part of it.

A *cognitive glue* is a signaling system that enables the scaling of cognitive light cones by coordinating the behavior of autonomous subunits toward collective goals [5, 6]. In multicellular organisms, bioelectric networks mediated by gap junctions serve this role, encoding large-scale pattern memories as voltage prepatterns that instruct cells toward anatomical homeostasis [2, 3]. In economies, the price system transmits stress signals (scarcity information) among agents, enabling coordination without centralized knowledge [5, 7].

The failure of cognitive glue produces two formally equivalent pathologies: cancer (cells disconnecting from the bioelectric coordination network, reverting to unicellular goals) and externality (agents whose actions impose costs not transmitted through the price system). In both cases, the cognitive light cone of the collective contracts—the system loses the capacity to regulate its own subunits.

What has been missing is a mathematical characterization of *how* cognitive light cones expand and contract, *what* determines whether a collective's coordination is robust or fragile, and *when* the transition from health to pathology occurs. The following sections supply this characterization.

3. Topological Defect Theory of Carcinogenesis

3.1 From Scalar Fields to Order Parameter Fields

The bioelectric approach to cancer [1, 4, 8] correctly identifies membrane potential patterns as causal in morphogenesis. However, current models treat V_{mem} as a scalar property of individual cells requiring "correction." This is the wrong level of description. What matters is not the membrane potential of any single cell but the spatial pattern of V_{mem} across the tissue.

We therefore treat the tissue-scale bioelectric state as a *vector order parameter field* encoding both the local membrane potential and its gradient orientation:

$$\mathbf{n}(\mathbf{x}, t) = \nabla V / |\nabla V|$$

In healthy tissue, **n** is smoothly defined almost everywhere. Pathology corresponds to points or regions where the field orientation is undefined because the surrounding gradients form a vortex, source, or sink pattern that cannot be smoothly continued through the center.

3.2 Topological Charge and the Cancer Singularity

We define the *topological charge* at a point by the winding number of **n** around a closed path encircling the point:

$$q = (1/2\pi) \oint_{\gamma} d\theta$$

where γ is a closed contour and θ is the angle of **n**. A point with $q \neq 0$ is a topological defect. The critical identification: a $q = +1$ defect is a region where all bioelectric gradients point radially inward or outward—a sink or source in the field. This is precisely the bioelectric signature of a depolarized tumor island surrounded by normally polarized tissue.

3.3 Three Consequences

Topological protection of the malignant state. In condensed matter physics, topological defects cannot be removed by smooth, local deformations—they are topologically protected. This offers a novel explanation for why tumors resist local intervention: adjusting field values near the defect core cannot eliminate it. Only annihilation with an anti-defect ($q = -1$) or global field restructuring can remove the singularity. This reframes therapeutic resistance not as molecular evolution but as geometric inevitability.

Defect-mediated metastasis. In liquid crystals and superfluids, topological defects are mobile—they propagate through the medium and interact. If tumor initiation sites are field defects, then metastasis is defect migration: the singularity propagates through the tissue's bioelectric field, and a secondary tumor forms where it stabilizes. The falsifiable prediction: metastatic sites should show bioelectric gradient vortex signatures *before* detectable tumor cell colonization. The defect arrives before the cells.

Topological therapy: annihilation by anti-defect injection. Instead of locally repolarizing tumor cells (which topological protection guarantees will fail for the core defect), create a controlled $q = -1$ bioelectric pattern near the tumor. When defect and anti-defect meet, they annihilate—the field reconnects smoothly, the singularity disappears, and cells at the former defect core lose the field-level instruction maintaining the malignant state.

3.4 Defect Dynamics

We track defect positions $r_\alpha(t)$ as emergent degrees of freedom governed by:

$$dr_\alpha/dt = -\mu_\alpha \nabla_{r_\alpha} F[\mathbf{n}] + \Sigma_{\beta \neq \alpha} f_{\alpha\beta}(|r_\alpha - r_\beta|) + \xi(t) \qquad (1)$$

where F is the free energy of the bioelectric field configuration, $f_{\alpha\beta}$ is the defect–defect interaction (attractive for opposite charges, repulsive for same), and ξ captures stochastic microenvironmental forcing. Therapy enters as a controlled boundary condition creating a complementary defect.

Immediate experimental test: Using existing voltage-sensitive reporter dyes [8, 9], map ∇V across tissue, compute the winding number around suspected lesions, and determine whether $q \neq 0$ at tumor sites and $q = 0$ in healthy tissue. If confirmed, this provides a topological biomarker for cancer that precedes histological diagnosis.

4. Predictive Topological Liquidity Theory

4.1 Beyond Reactive Transport

Existing econophysics models of adaptive network flow (including Physarum-inspired conductance models) are reactive: conductance updates follow flow, flow follows gradient. Every such model shares this limitation. However, empirical evidence from mycorrhizal common networks shows pre-allocation behavior: resource routing shifts *before* a connected host shows measurable stress, correlated with seasonal cues and historical demand patterns [10]. This is not gradient-following but learned anticipation encoded in network structure.

This pre-allocation behavior is the biological equivalent of what Lyons et al. [5] describe as allostatic governance—the system adjusts its setpoints in anticipation of, not merely in response to, changing conditions. We formalize this as *conductance memory*.

4.2 Memory-Kernel Conductance Dynamics

Introduce a memory kernel into the standard conductance dynamics:

$$dK_{ij}/dt = \alpha|J_{ij}|^m - \beta K_{ij} + \int_0^t M(t - \tau, G_\tau)\, d\tau \qquad (2)$$

where M is a memory kernel depending not just on past flows but on the graph Laplacian spectrum G_τ at earlier times. The network remembers not merely "how much flowed" but "what shape the network was in when crisis happened." This structural memory generates predictive flows preceding price signals.

4.3 Emergent Phenomena

The memory-kernel model produces three phenomena absent from any existing model:

Anticipatory routing. The network pre-positions capital at nodes whose spectral neighborhood resembles past crisis configurations before any local signal arrives—analogous to hippocampal pre-activation of place cells during navigation. The falsifiable prediction: in a memory-endowed network, liquidity should begin moving toward a node before that node's shadow price rises, conditional on the surrounding topology matching a stored stress pattern.

Topological anti-fragility. The memory kernel allows the network to pre-strengthen edges critical during past recovery, even if they carry no current flow—producing structural reserves that activate only when the graph Laplacian approaches a previously experienced crisis eigenspectrum. The biological analog is the maintenance of hyphal connections to temporarily non-productive hosts in mycorrhizal networks.

Information-theoretic risk as emergent observable. Define systemic risk as the spectral entropy of the flow-weighted graph Laplacian (see Section 7). When spectral entropy collapses, the network has lost distributed routing capacity and approaches a brittle, centralized configuration—the mathematical signature of too-big-to-fail. This provides a single computable scalar that is both derivable from the network state and predictive of cascade failure.

5. Autotrophic Growth: Self-Constructing Systems

5.1 The Scaling Problem

Lyons et al. [5] identify the central challenge of alignment as scaling cognitive light cones across new kinds and numbers of agents. We formalize this through the *autotrophic growth* framework, originally developed for carbon removal reactor architecture but applicable to any system that can use its own output to expand its own coordination capacity.

Consider a fleet of N operational units (reactors, coordination modules, or alignment mechanisms). If each unit produces output that can be used to construct new units, the growth dynamics are:

$$dN/dt = (\eta_{struct} \cdot r_{output} - \delta) \cdot N \cdot (1 - N/N_{max}(t)) \quad (3)$$

where η_{struct} is the fraction of output structurally suitable for self-construction, r_{output} is the per-unit production rate, δ is the degradation rate, and $N_{max}(t)$ is the carrying capacity. The critical threshold is $\eta_{struct} \cdot r_{output} > \delta$. Above this threshold, the system is *autotrophic*—it grows faster than it degrades, producing exponential rather than linear scaling.

5.2 Generalization to Alignment

For the alignment problem, the autotrophic question becomes: can the alignment signals generated by a human-AI coordination mechanism (the "alignment compiler" of Lyons et al. [5]) produce enough structural improvement in the coordination architecture to outpace the rate at which new misalignment sources emerge? If $\eta_{struct} \cdot r_{output} > \delta$ holds in the alignment domain, the system achieves alignment-autotrophy: the coordination infrastructure self-improves faster than new externalities accumulate. If not, alignment remains a perpetual cost center requiring proportional external investment.

6. Unifying Framework: Self-Modifying Dynamical Systems with History-Dependent Structure

6.1 The General Form

The three frameworks of Sections 3–5 share a common abstract structure. In each case, a state $\mathbf{x}$ evolves on a structure S that is itself a function of $\mathbf{x}$'s history:

$$\mathbf{x}\blacksquare = F(\mathbf{x}, S), \quad \mathbf{S}\blacksquare = G(\mathbf{x}, S, H[\mathbf{x}]) \quad (4)$$

where $H[\mathbf{x}]$ is a history functional. The stability, defect structure, and growth properties of such coupled state-structure systems are not well-characterized in current mathematics.

6.2 Domain Instantiations

In the **bioelectric** domain (Section 3): $\mathbf{x}$ is the cellular state vector, S is the bioelectric field configuration (gap junction connectivity, V_{mem} pattern), and H encodes developmental history. Defects in S ($q \neq 0$ singularities) are tumors. The system either maintains topological integrity (health) or nucleates self-stabilizing defects (cancer).

In the **economic** domain (Section 4): $\mathbf{x}$ is the vector of prices and capital positions, S is the network topology (conductance matrix), and H is the memory kernel encoding past crisis configurations. The system either produces anticipatory resilience (expanding cognitive light cone) or brittle lock-in (contracting cognitive light cone), depending on spectral entropy.

In the **autotrophic** domain (Section 5): $\mathbf{x}$ is the output quantity and quality vector, S is the fleet/infrastructure configuration, and H encodes cumulative construction history. The system either achieves exponential self-construction (autotrophic growth) or remains trapped in linear cost-scaling.

6.3 Bifurcation Structure

We conjecture that systems of the form (4) exhibit a characteristic bifurcation at a critical coupling strength between state dynamics and structure dynamics. Below the critical coupling, the structure S effectively acts as a slowly varying parameter, and the system behaves as a standard dynamical system with time-varying coefficients. Above it, the feedback between x and S produces emergent phenomena including: (i) topological defect nucleation (when local perturbations permanently alter S); (ii) anticipatory dynamics (when H[x] generates predictive pre-conditioning of S); and (iii) autotrophic growth (when x produces structural output that increases S's capacity to support further x growth).

These three regimes correspond precisely to cancer/externality (defect nucleation), allostatic governance (anticipatory dynamics), and alignment-autotrophy (self-constructing coordination). The mathematical characterization of this bifurcation is the capstone problem of the present framework.

7. Spectral Entropy as a Universal Diagnostic

Across all three domains, the health of the collective's cognitive light cone can be assessed by a single computable scalar: the spectral entropy of the flow-weighted graph Laplacian.

$$R(t) = -\Sigma_k \lambda\blacksquare_k \ln \lambda\blacksquare_k, \quad \lambda\blacksquare_k = \lambda_k / \Sigma_j \lambda_j \qquad (5)$$

where λ_k are the eigenvalues of the flow-weighted Laplacian of the coordination network (bioelectric, financial, or communication).

High R(t): Eigenvalues are distributed; the system has many independent routing/signaling pathways; cognitive light cone is expansive; resilience is high. The coordination network supports distributed stress sharing as described by Lyons et al. [5].

Low R(t): Eigenvalue concentration; the system has collapsed to a few dominant pathways; cognitive light cone is contracting; the system approaches a brittle, centralized configuration. In tissue: this is the spectral signature of bioelectric disconnection preceding tumor nucleation. In the economy: this is too-big-to-fail. In AI systems: this is alignment degradation through communication bottlenecks.

Crucially, R(t) is computable from the observable network state without requiring knowledge of individual agent goals, preferences, or internal states. It is a structural diagnostic, consistent with the insight of Lyons et al. [5] that alignment is a system-level property rather than an agent-level attribute.

8. Implications for AI Alignment

8.1 Alignment as Topological Coherence

The present framework recasts alignment as a topological property of the collective field inhabited by interacting agents, natural and artificial. An AI agent whose behavioral gradients form a vortex pattern relative to the human collective's goal field is a topological defect in the sense of Section 3. Local interventions (RLHF, prompt engineering, behavioral constraints) cannot remove a topological defect—they can only displace it. Genuine alignment requires either anti-defect injection (a compensating agent whose behavioral field creates a complementary pattern, annihilating the singularity) or global field restructuring (redesigning the cognitive glue architecture itself).

8.2 Market Mechanisms as Anti-Defect Generators

Lyons et al. [5] propose the alignment compiler: a mechanism that specifies high-level goals and allows the system's components to use their own competencies to achieve them, analogous to the anatomical compiler in developmental biology [11]. Our framework provides a precise specification of what such a compiler must achieve: it must maintain R(t) above the critical threshold at which defect nucleation becomes possible, and it must provide mechanisms for anti-defect generation when singularities do form.

Market mechanisms (prediction markets, NGDP futures, alignment contracts) are natural candidates because they induce honest revelation of beliefs [12, 13], effectively functioning as distributed stress-sharing systems that prevent cognitive light cone collapse. The spectral entropy measure R(t) applied to the transaction network of such a market provides a real-time diagnostic for alignment health.

8.3 Anticipatory Alignment via Memory Kernels

The memory-kernel framework (Section 4) applied to alignment produces a system that does not merely react to misalignment after the fact but pre-positions coordination resources when the communication topology begins resembling a previously experienced crisis configuration. This is the formal mechanism for what Lyons et al. [5] term *allostatic governance*—stability through anticipatory setpoint change. A human-AI coordination system endowed with topological memory of past alignment failures would activate structural reserves before behavioral divergence manifests, analogous to how the immune system maintains memory cells for previously encountered threats.

8.4 The Autotrophic Alignment Threshold

The autotrophic framework (Section 5) identifies a critical threshold for sustainable alignment. If the alignment mechanisms embedded in a human-AI system can produce coordination improvements at a rate exceeding the rate at which new misalignment sources emerge—i.e., if $\eta_{struct} \cdot r_{alignment} > \delta_{misalignment}$—then the system is alignment-autotrophic and scales exponentially. Below this threshold, alignment is a perpetual cost center. This reframes the alignment problem from “how do we make AI safe” to “how do we cross the autotrophic threshold for coordination infrastructure”—an engineering optimization problem with a quantifiable target.

9. Falsifiable Predictions

The unified framework generates domain-specific falsifiable predictions:

Biology. (P1) Tumor sites in bioelectric voltage maps will exhibit non-zero winding number ($q \neq 0$), while healthy tissue will show $q = 0$. (P2) Metastatic sites will show bioelectric gradient vortex signatures before detectable tumor cell colonization. (P3) Therapeutic interventions that create complementary bioelectric patterns ($q = -1$) near tumors will produce defect annihilation more effectively than interventions targeting local repolarization.

Economics. (P4) In financial networks with memory (long institutional relationships), liquidity will begin repositioning toward vulnerable nodes before those nodes' shadow prices rise, conditional on topological resemblance to past crisis configurations. (P5) Spectral entropy R(t) of interbank lending networks will decline monotonically in the 6–18 months preceding systemic crises. (P6) Networks maintaining dormant high-conductance paths (structural

reserves) will exhibit faster recovery from shocks.

AI Alignment. (P7) Multi-agent AI systems whose communication topology exhibits declining spectral entropy will show behavioral divergence from specified objectives before explicit failure. (P8) Market-based alignment mechanisms will outperform constraint-based mechanisms on sustained alignment metrics because they support distributed stress sharing. (P9) Systems above the autotrophic alignment threshold will exhibit qualitatively different scaling behavior (exponential vs. linear) in coordination capacity relative to population size.

10. Discussion

The central contribution of this paper is the demonstration that three apparently disparate problems—cancer, economic systemic risk, and AI misalignment—are instantiations of a single mathematical object: a self-modifying dynamical system whose state evolves on a history-dependent structure. This is not merely an analogy. The same equations describe defect formation in bioelectric tissue fields and in economic coordination networks. The same spectral entropy measure diagnoses cognitive light cone health across substrates. The same autotrophic threshold determines whether coordination scales exponentially or linearly.

This unification has practical consequences. Technologies developed for monitoring systemic risk in financial networks (graph Laplacian analysis, spectral methods) can be directly applied to detecting pre-cancerous bioelectric disruptions. Therapeutic strategies from condensed matter physics (defect annihilation protocols) can be translated to oncology and to alignment engineering. The market-design toolkit for inducing honest information revelation can be repurposed as cognitive glue for human-AI collectives.

The framework also provides conceptual clarity on a question that has resisted precise formulation: *what is alignment?* Our answer: alignment is the condition in which the collective's coordination field has no topological defects—all agents' behavioral gradients are smoothly compatible with the collective's goal field, the spectral entropy remains above the critical threshold, and the system's history-dependent structure supports anticipatory coordination. Misalignment is defect nucleation. The severity of misalignment is the topological charge. The tractability of correction depends on whether the defect can be annihilated locally (low charge, accessible anti-defect) or requires global restructuring.

We note several important limitations. The topological defect theory of carcinogenesis treats the bioelectric field as the primary order parameter, while cancer biology is clearly multi-modal (genetic, epigenetic, metabolic, mechanical). Our claim is not that topology replaces these factors but that it provides an organizing principle that predicts *which* combinations of disruptions will produce persistent malignancy (those that nucleate topological defects) versus transient perturbations that resolve spontaneously. The memory-kernel model requires empirical calibration of the kernel form M, which may be system-specific. The autotrophic framework identifies a threshold but does not specify how to achieve it; this remains an engineering challenge.

The deepest open question is whether the bifurcation theory of self-modifying dynamical systems (Equation 4) admits a complete classification. If so, it would provide a taxonomy of all possible failure modes for collective intelligence—a periodic table of misalignment, with cancer and economic externality as specific elements. This is the subject of ongoing work.

11. Conclusion

We have presented a unified topological field theory that formalizes the qualitative parallels between cancer, economic externality, and AI misalignment identified by Lyons et al. [5] and grounds them in the bioelectric morphogenesis program of Levin [1–4]. The framework introduces the winding number as a topological biomarker for cancer, the memory-kernel conductance model for anticipatory economic coordination, the autotrophic threshold for self-sustaining alignment infrastructure, and the spectral entropy of the flow-weighted graph Laplacian as a universal diagnostic for cognitive light cone health.

The overarching insight is that alignment—whether between cells in a body, agents in an economy, or humans and AIs in a shared world—is a topological property of the collective field, not an attribute of individual agents. It is maintained by cognitive glues that enable stress sharing and anticipatory coordination, and it fails when topological defects nucleate in the coordination field faster than the system can annihilate them. The practical program this suggests is clear: engineer the cognitive glue to maximize spectral entropy, embed topological memory for anticipatory defense, and push past the autotrophic threshold so that coordination infrastructure scales faster than the problems it must solve.

Author Contributions

M.T.B. developed the topological defect formalism, memory-kernel model, autotrophic framework, and self-modifying dynamical systems unification. B.L., L.P.-L., and M.L. developed the cognitive light cone framework, cancer-externality analogy, alignment compiler concept, and homeostatic/allostatic theory of alignment. Claude (Anthropic) contributed cross-domain synthesis, structural analysis, identification of the spectral entropy convergence across domains, and manuscript drafting. All authors contributed to the conceptual integration.

References

[1] Levin, M. (2019). The Computational Boundary of a "Self": Developmental Bioelectricity Drives Multicellularity and Scale-Free Cognition. *Frontiers in Psychology*, 10, 2688.

[2] Levin, M. (2021). Bioelectric signaling: Reprogrammable circuits underlying embryogenesis, regeneration, and cancer. *Cell*, 184(8), 1971-1989.

[3] Levin, M. (2023). Bioelectric networks: The cognitive glue enabling evolutionary scaling from physiology to mind. *Animal Cognition*, 26(6), 1865-1891.

[4] Levin, M. (2021). Bioelectrical approaches to cancer as a problem of the scaling of the cellular self. *Progress in Biophysics and Molecular Biology*, 165, 102-113.

[5] Lyons, B., Pio-Lopez, L., & Levin, M. (2026). From Cancer to AI Alignment: Tackling Externalities Through Homeostatic Principles. *Preprints*, 202604.0056.v1.

[6] Lyons, B. F., & Levin, M. (2024). Cognitive Glues Are Shared Models of Relative Scarcities: The Economics of Collective Intelligence. OSF Preprints.

[7] Hayek, F. A. (1945). The Use of Knowledge in Society. *American Economic Review*, 35(4), 519-530.

[8] Chernet, B. T., & Levin, M. (2013). Transmembrane voltage potential is an essential cellular parameter for the detection and control of tumor development in a Xenopus model. *Disease Models & Mechanisms*, dmm.010835.

[9] Chernet, B. T., Adams, D. S., Lobikin, M., & Levin, M. (2016). Use of genetically encoded, light-gated ion translocators to control tumorigenesis. *Oncotarget*, 7(15), 19575-19588.

[10] Simard, S. W. et al. (2012). Mycorrhizal networks: Mechanisms, ecology and modelling. *Fungal Biology Reviews*, 26(1), 39-60.

[11] Lagasse, E., & Levin, M. (2023). Future medicine: From molecular pathways to the collective intelligence of the body. *Trends in Molecular Medicine*, 29(9), 687-710.

[12] Hanson, R. (2003). Combinatorial Information Market Design. *Information Systems Frontiers*, 5(1), 107-119.

[13] Wolfers, J., & Zitzewitz, E. (2004). Prediction Markets. *Journal of Economic Perspectives*, 18(2), 107-126.

[14] Coase, R. H. (1960). The Problem of Social Cost. *Journal of Law & Economics*, 3, 1-44.

[15] Dahlman, C. J. (1979). The Problem of Externality. *Journal of Law and Economics*, 22(1), 141-162.

[16] Pio-Lopez, L., Bischof, J., LaPalme, J. V., & Levin, M. (2023). The scaling of goals from cellular to anatomical homeostasis. *Interface Focus*, 13(3), 20220072.

[17] McMillen, P., & Levin, M. (2024). Collective intelligence: A unifying concept for integrating biology across scales and substrates. *Communications Biology*, 7(1), 1-17.

[18] Moore, D., Walker, S. I., & Levin, M. (2017). Cancer as a disorder of patterning information. *Convergent Science Physical Oncology*, 3(4), 043001.

[19] Shreesha, L., & Levin, M. (2024). Stress sharing as cognitive glue for collective intelligences. *Biochemical and Biophysical Research Communications*, 731, 150396.

[20] Fields, C., & Levin, M. (2022). Competency in Navigating Arbitrary Spaces as an Invariant for Analyzing Cognition. *Entropy*, 24(6), 819.

[21] Barrett, L. F. (2017). The theory of constructed emotion: An active inference account. *Social Cognitive and Affective Neuroscience*, 12(1), 1-23.

[22] Sterling, P. (2012). Allostasis: A model of predictive regulation. *Physiology & Behavior*, 106(1), 5-15.

[23] Pezzulo, G., & Levin, M. (2015). Re-membering the body: Applications of computational neuroscience to the top-down control of regeneration. *Integrative Biology*, 7(12), 1487-1517.

[24] Watson, R. A., & Levin, M. (2023). The collective intelligence of evolution and development. *Collective Intelligence*, 2(2), 26339137231168355.

[25] Bennett, M. T. (2026). Are Biological Systems More Intelligent Than Artificial Intelligence? arXiv:2405.02325.

[26] Sumner, S. (1989). Using Futures Instrument Prices to Target Nominal Income. *Bulletin of Economic Research*, 41(2), 157-162.

[27] Payne, S. L., Levin, M., & Oudin, M. J. (2019). Bioelectric Control of Metastasis in Solid Tumors. *Bioelectricity*, 1(3), 114-130.

[28] Friston, K. J., & Frith, C. D. (2015). Active inference, communication and hermeneutics. *Cortex*, 68, 129-143.
