

Mathematical Structures as Explanatory Frameworks Across Biological and Physical Systems



Arturo Tozzi

MATHEMATICAL STRUCTURES AS EXPLANATORY FRAMEWORKS ACROSS BIOLOGICAL AND PHYSICAL SYSTEMS

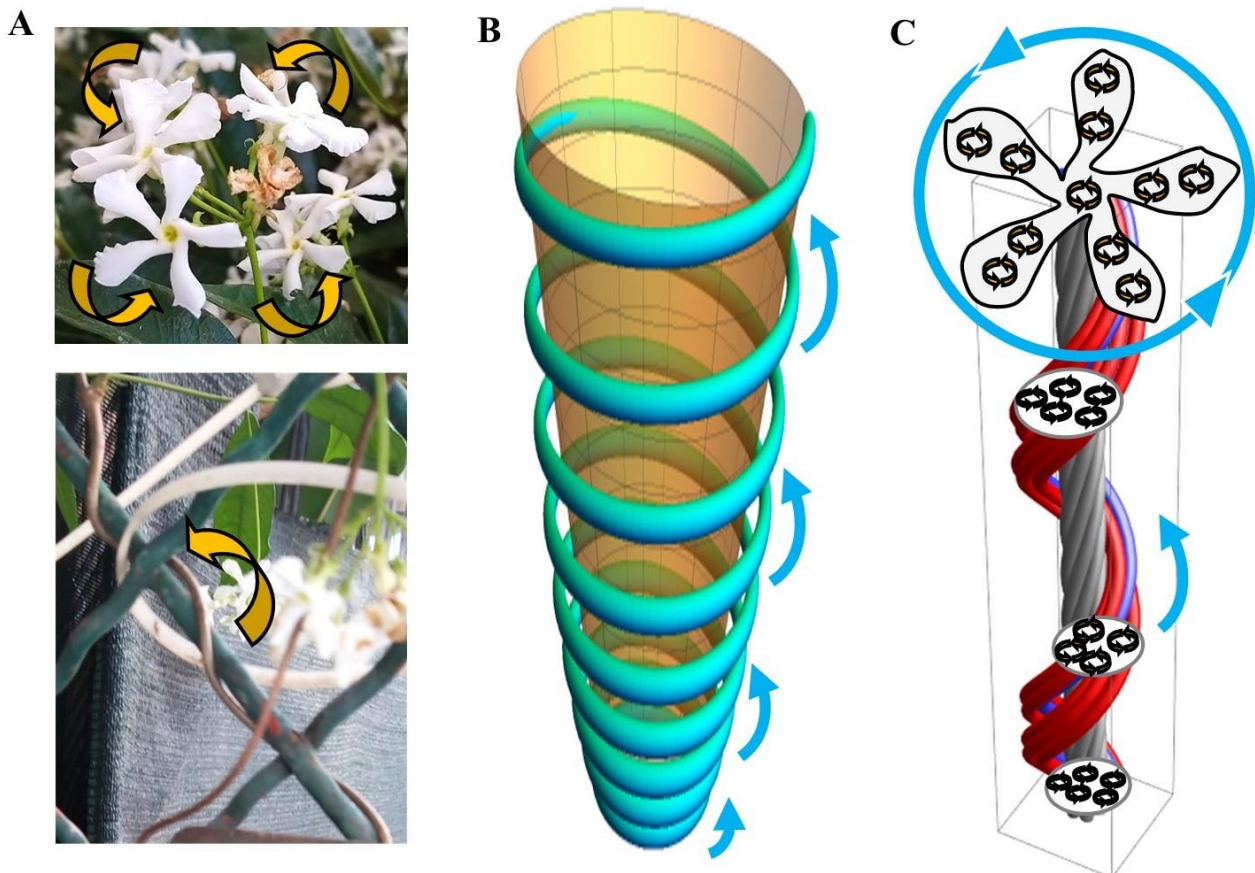
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A recurring strategy in our work is to apply mathematical issues to physical, biological and cognitive systems to reveal structural invariants and hidden constraints in their organization and dynamics. Rather than building ad hoc models for specific phenomena, we reinterpret complex processes as instances of geometric spaces, topological invariants, symmetries, algebraic structures, information-theoretic measures, logical systems, etc. Applications span many areas. Topological and geometric frameworks help describe biological networks, vascular systems, morphogenetic processes and neural representations. Algebraic and logical models help analyze regulatory interactions, causal relations and epistemic transitions in physical theories. Information-theoretic and statistical methods can reveal hidden organizational regimes in complex systems. Therefore, mathematical structures provide explanatory frameworks that reveal the architecture of complex systems, connect local interactions to global organization, and generate experimentally testable predictions.

MATHEMATICAL STRUCTURES IN BIOLOGICAL SYSTEMS

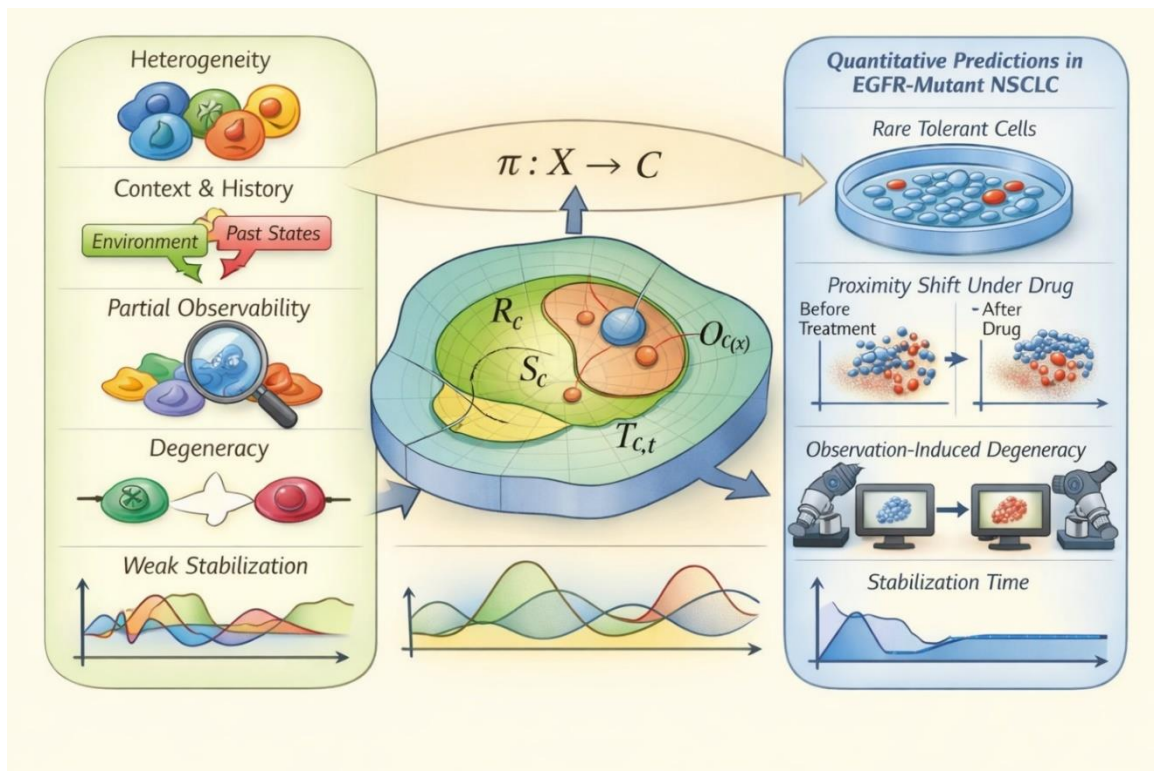
Tozzi A. 2025. Local Topological Structures and Global Connectivity Patterns in a *Trachelospermum jasminoides*: a Pilot Study. BioRxiv. doi: <https://doi.org/10.1101/2025.02.04.636494>.

This study applies topological data analysis, combining persistent homology, graph theory, spectral analysis, percolation theory and Delaunay triangulation to quantify how local plant structures generate resilient global connectivity patterns in biological growth networks.



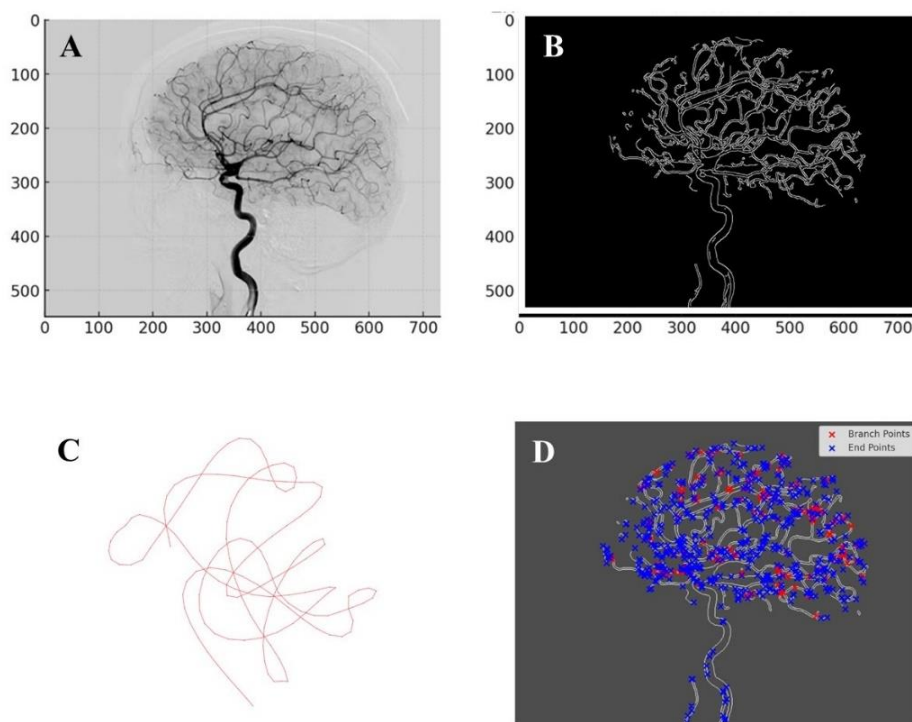
Tozzi A. 2025. Architectural Dynamics in Living Tissues: Integrating Structure, Physical Fields and Spatial Networks. Preprints. <https://doi.org/10.20944/preprints202512.0608.v1>.

This study integrates spatial network topology and physical-field modeling to analyze tissue architecture, treating living tissues as interacting structural networks embedded in physical fields that constrain cellular organization and morphogenetic dynamics.



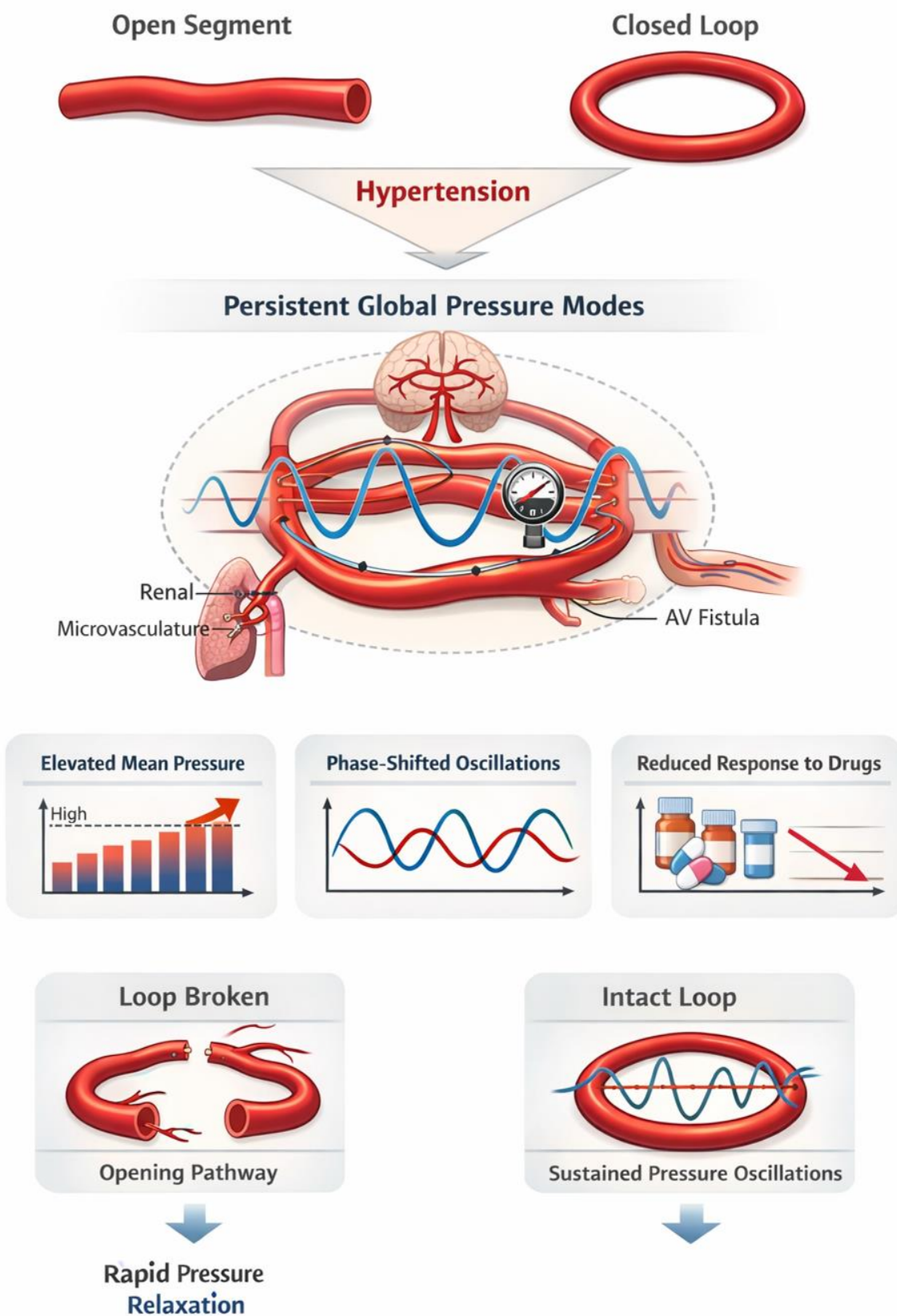
Tozzi A. 2025. Topological Analysis of Vascular Networks: A Proof-of-Concept Study in Cerebral Angiography. Preprints. <https://doi.org/10.20944/preprints202502.0724.v1>.

This study applies algebraic and differential topology to cerebral angiography, using graph representations, Betti numbers, homotopy equivalence and Fourier decomposition to quantify vascular connectivity, loops and structural stability in cerebrovascular networks.



Tozzi A. 2026. Towards a topological view of blood pressure regulation. arXiv:2602.10011.

This paper applies topological analysis of vascular loops to blood pressure regulation, modeling the circulatory system as networks of quasi-closed flow loops and showing how global vascular topology constrains pressure dynamics beyond local resistance or compliance mechanisms.

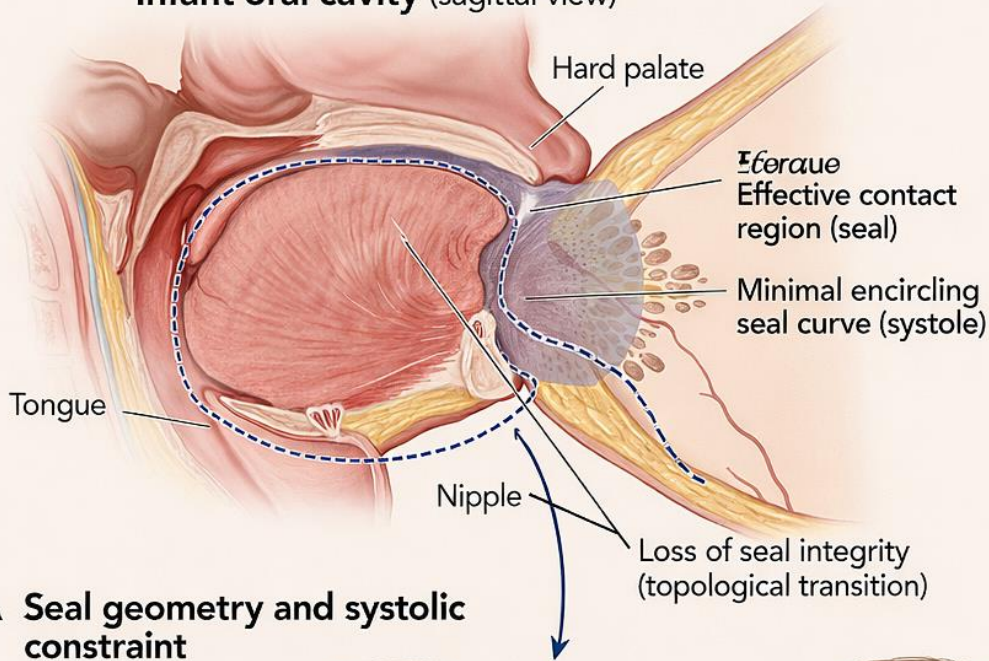


Tozzi A. 2026. Geometric and topological constraints on oral seal formation during infant breastfeeding. arXiv:2602.17389.

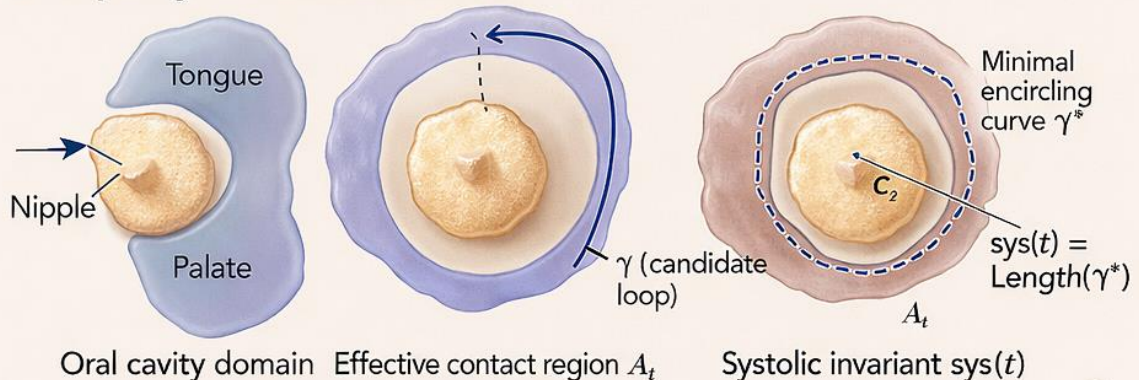
This study applies systolic geometry and homological analysis to infant breastfeeding. Oral seal formation is modeled as a minimal non-contractible loop encircling the nipple, identifying topological constraints required for stable circumferential sealing during feeding.

GEOMETRIC AND TOPOLOGICAL CONSTRAINTS ON ORAL SEAL FORMATION DURING INFANT BREASTFEEDING

Infant oral cavity (sagittal view)



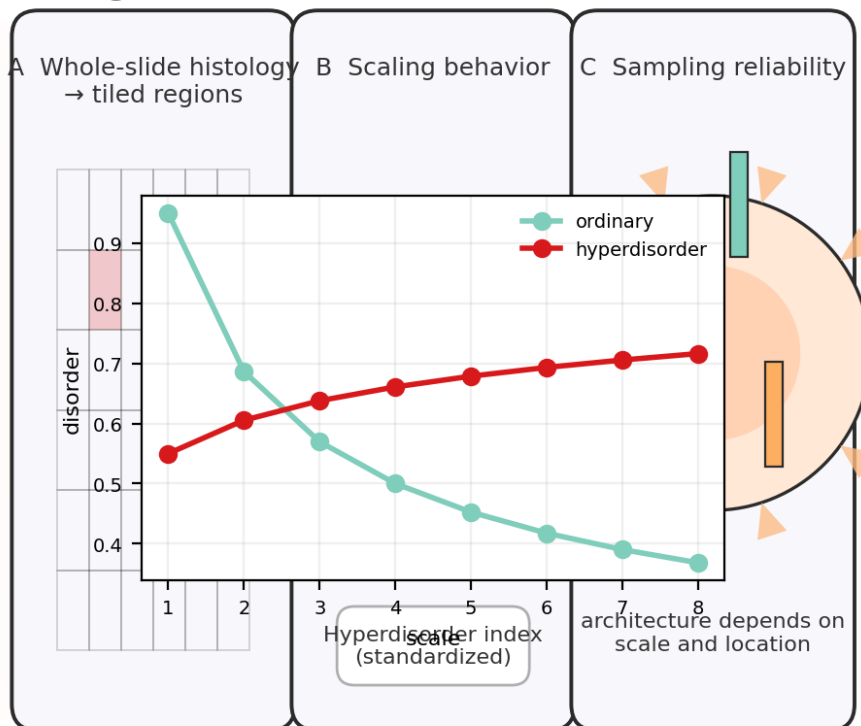
B Topological seal transition



Koczkodaj, W. W.; Pigazzini, A.; Tozzi, A. 2024. Geometric Properties and Hand Grasping Dynamics: a Useful Approach to Bionic Hands. Preprints 2024, 2024101202. <https://doi.org/10.20944/preprints202410.1202.v1>.
 This study applies topological phase-space dynamics to bionic hand control, modeling motor configurations as trajectories in structured state spaces where attractors and transitions constrain prosthetic movement and coordination.

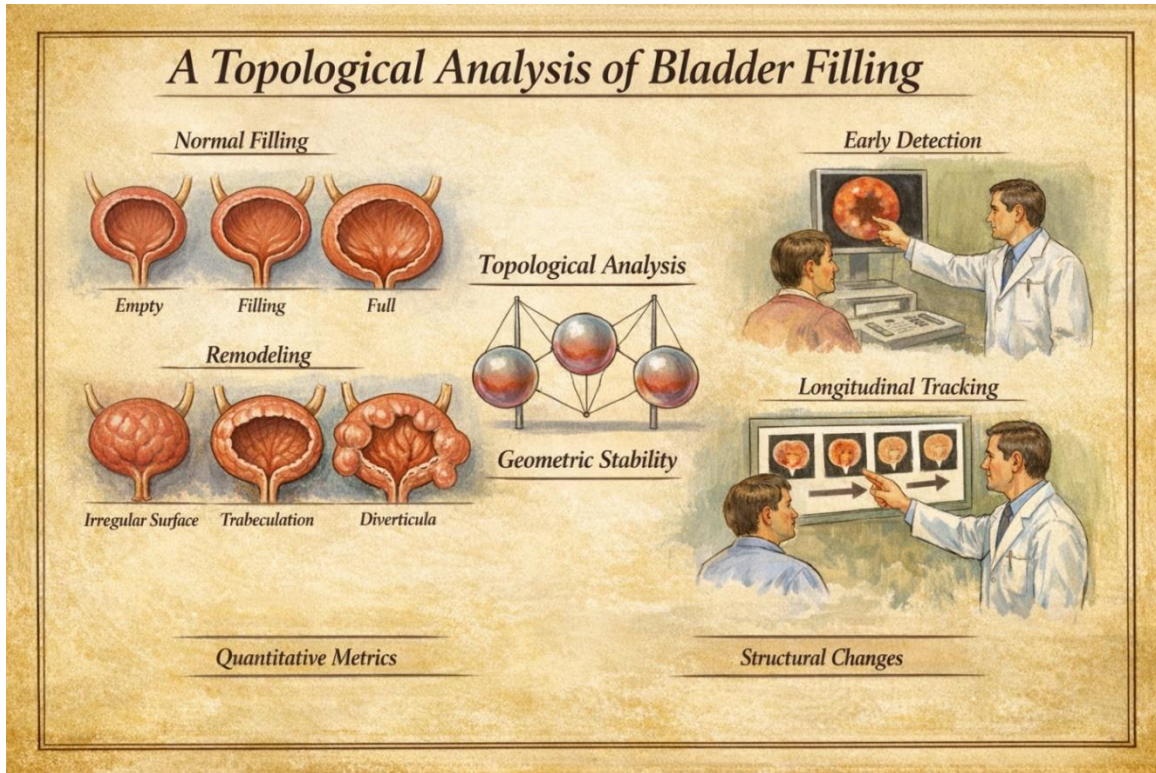
Tozzi A. 2026. Hyperdisorder in tumor growth. arXiv:2601.19852.
 This study applies multiscale entropy and spatial scaling analysis to tumor histology, introducing hyperdisorder, i.e., a regime where architectural disorder persists or increases across scales rather than averaging out under spatial coarse-graining.

Hyperdisorder as growth-driven multiscale incoherence in tumor histology



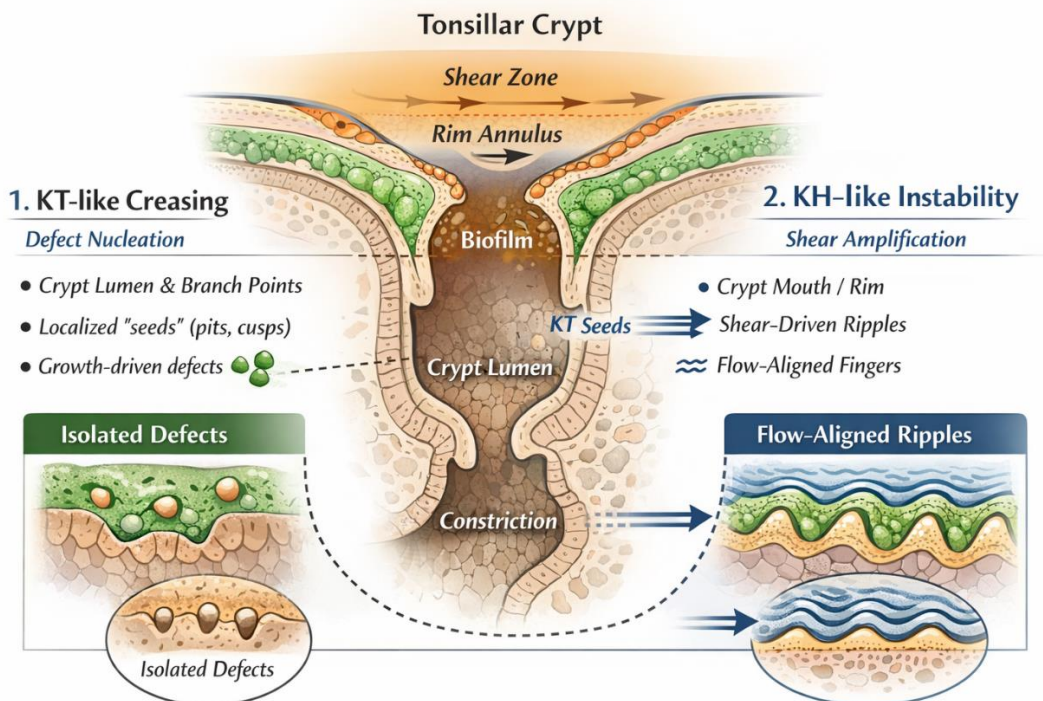
Tozzi A. Topological analysis of bladder filling. arXiv:2603.01054

This study applies a topological framework inspired by the Freudenthal suspension theorem to bladder filling, modeling volume increase as dimensional expansion and identifying geometric invariants that distinguish structural reorganization from purely mechanical pressure–volume changes.



Tozzi A. 2026. From local defects to shear-organized biofilms in tonsillar crypts via computational simulations. arXiv:2601.07863.

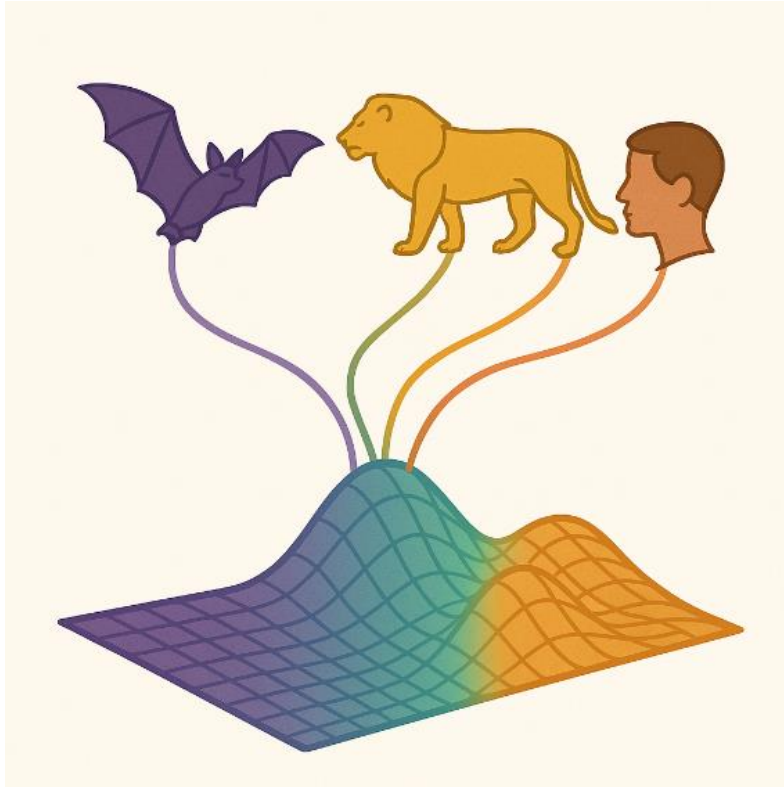
This study uses computational simulations of defect-driven self-organization and shear-induced pattern formation to model bacterial biofilms in tonsillar crypts, showing how local structural defects generate organized biofilm structures under fluid shear.



MATHEMATICAL APPROACHES TO THE BRAIN

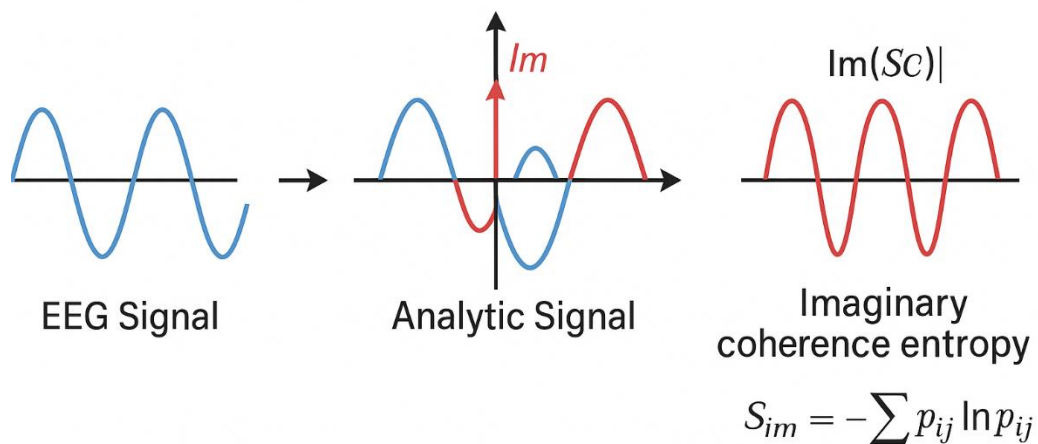
Tozzi, A. 2025. Exploring Neural Mechanisms Underlying High-Dimensional Brain Activity. Preprints. <https://doi.org/10.20944/preprints202506.0434.v1>.

This study applies topological dynamics and synthetic dimensionality modeling, using oscillatory interference and phase-modulated lattice systems to simulate higher-dimensional neural computations, suggesting cortical oscillations encode information in effective four-dimensional representational spaces.



Tozzi A. 2025. Imaginary Entropy in Human Eeg Traces. Preprints. <https://doi.org/10.20944/preprints202511.0025.v1>.

This study applies complex-valued entropy analysis to EEG signals, introducing imaginary entropy as a metric to capture phase-related information in neural dynamics that standard real-valued entropy measures cannot detect.

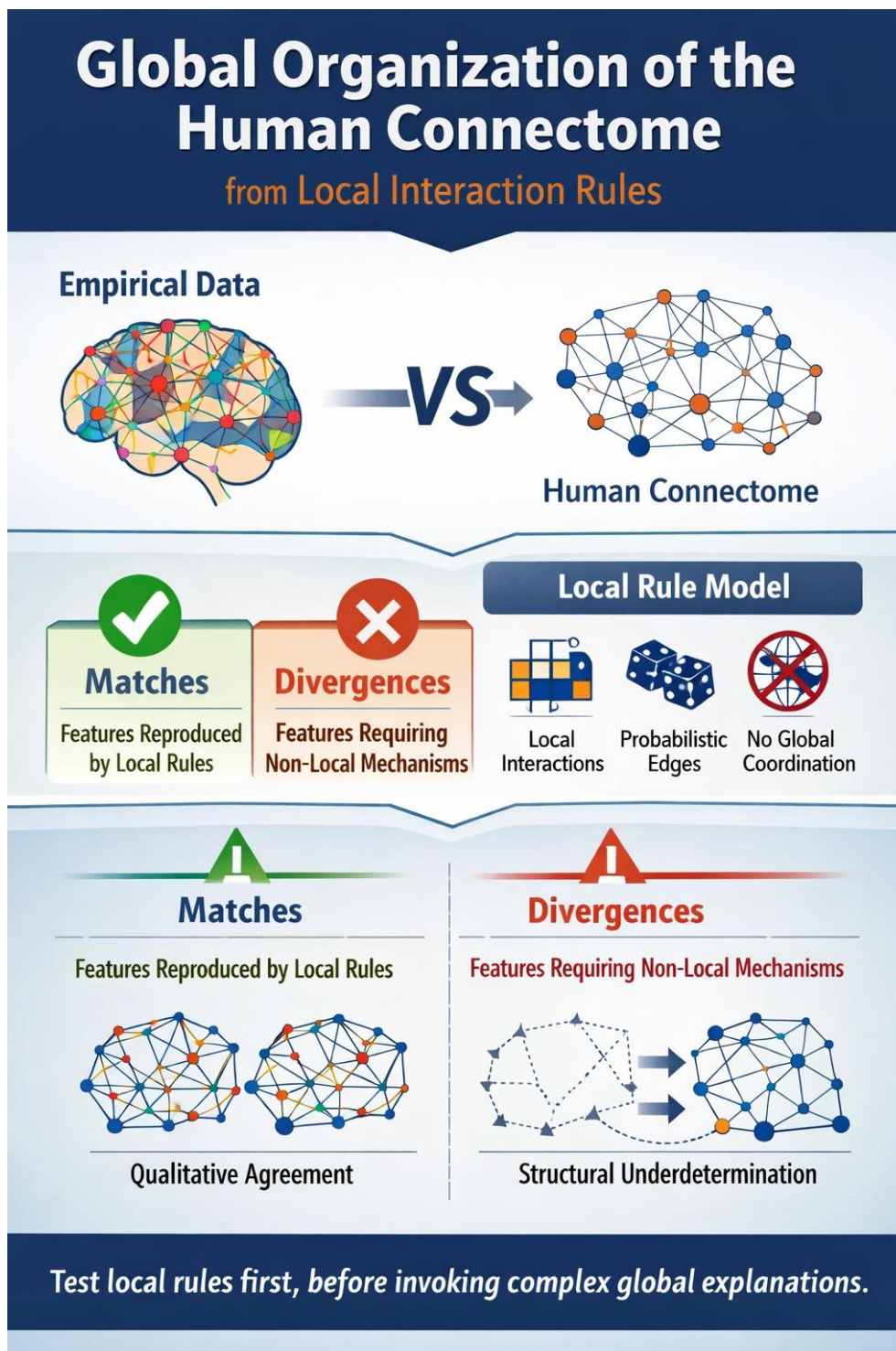


Tozzi A. 2025. Levy Flight Patterns in the Cortical Architecture of Macaca mulatta. bioRxiv 2025.01.29.635444; doi: <https://doi.org/10.1101/2025.01.29.635444>.

This study applies Lévy-flight statistics and power-law step-length distributions to cortical histological images, showing that spatial transitions in primate cortex follow heavy-tailed diffusion patterns characteristic of superdiffusive Lévy dynamics.

Tozzi, A. 2026. Local Interaction Rules Drive Global Organization of the Human Connectome. Preprints. <https://doi.org/10.20944/preprints202601.0075.v1>.

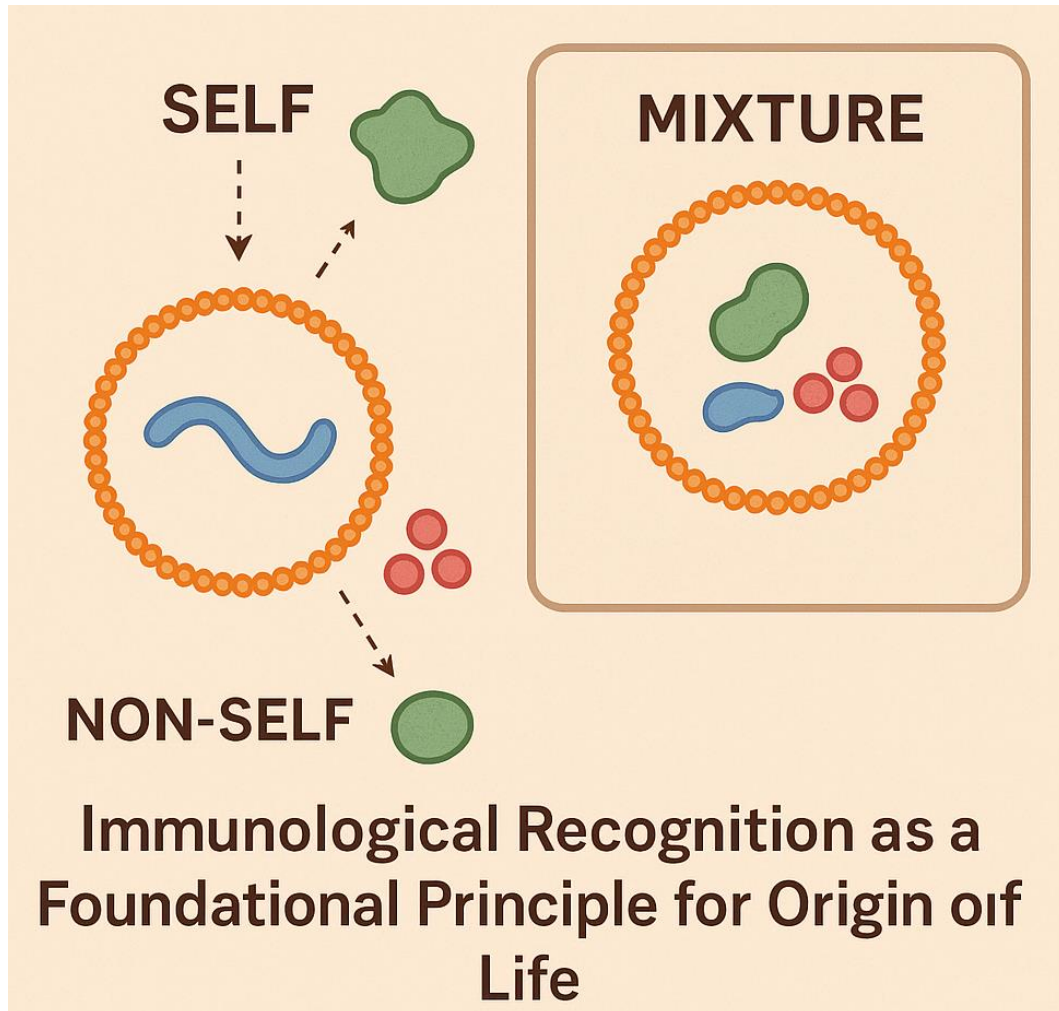
This study applies network theory and local-rule generative models to the human connectome, showing how simple local connectivity rules produce emergent global brain organization and large-scale network structure.



LOGIC AND ALGEBRA IN BIOLOGICAL AND PHYSICAL PROCESSES

Tozzi A. 2025. A Multi-Valued Logic Model of T Cell Activation and Cytokine Response. Preprint. Posted April 5, 2025. <https://doi.org/10.1101/2025.04.05.647356>.

This study applies multi-valued logic modeling to T-cell activation, representing regulatory inputs with discrete states (low, intermediate, high) to capture nonlinear immune decision dynamics beyond binary Boolean signaling models.



Tozzi A. 2025. Applications of Wedderburn's Theorem in Modelling Non-Commutative Biological and Evolutionary Systems. Preprint. Posted April 3, 2025. <https://doi.org/10.1101/2025.04.03.647006>.

This study applies the Wedderburn–Artin theorem from non-commutative algebra, decomposing biological interaction algebras into matrix blocks to analyze order-dependent processes such as transcription-factor binding and evolutionary mutation sequences.

Tozzi A. 2025. Coordination Logic: Modeling Dual Description Without Causal Assumptions. Preprints. <https://doi.org/10.20944/preprints202509.1602.v1>.

This study introduces coordination logic, a formal framework modeling relationships between descriptive domains without causal assumptions, representing systems through coordinated mappings that preserve structural correspondences between different observational descriptions.

Tozzi, A. 2025. Probabilistic Modal Logic for Quantum Dynamics. Preprints.

<https://doi.org/10.20944/preprints202505.1207.v1>

This study introduces Probabilistic Modal Logic for Quantum Dynamics, extending modal logic K with probabilistic operators to formalize epistemic transitions in quantum systems, capturing shifts from possibility to necessity during measurement.

Tozzi A, Planat M. 2025. Bridging General Relativity and Quantum Dynamics Through Finite-Resource Logical Models. arXiv:2503.23136

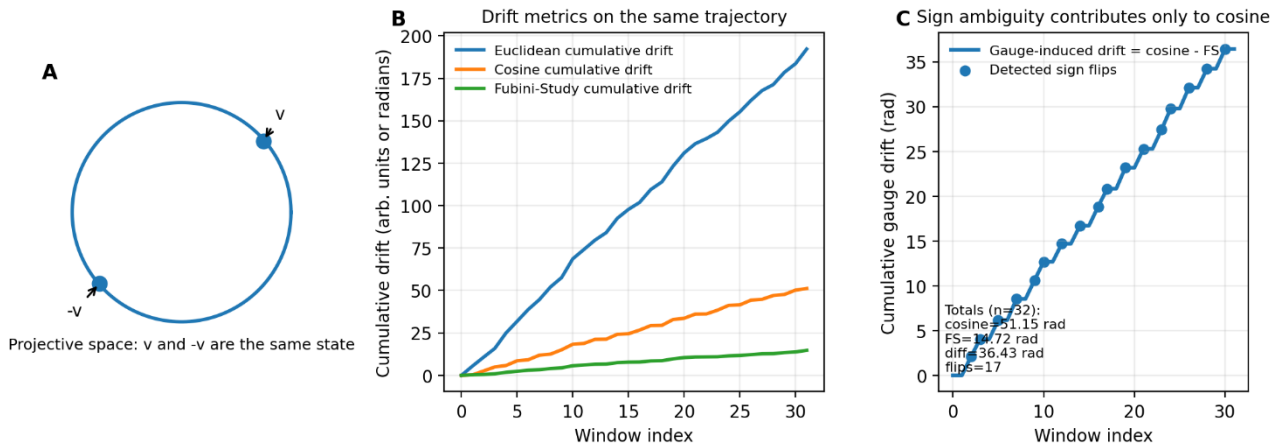
This study applies linear logic and Kripke semantics with finite-resource constraints, modeling causality, energy and information as non-replicable logical resources, providing a logical framework linking transitions in quantum dynamics and general relativity.

MATHEMATICAL MODELING OF LEARNING, ORGANIZATION, KNOWLEDGE, ARTIFICIAL AND COMPUTATIONAL SYSTEMS

Tozzi A. 2026. Fubini Study geometry of representation drift in high dimensional data. arXiv:2602.02596.

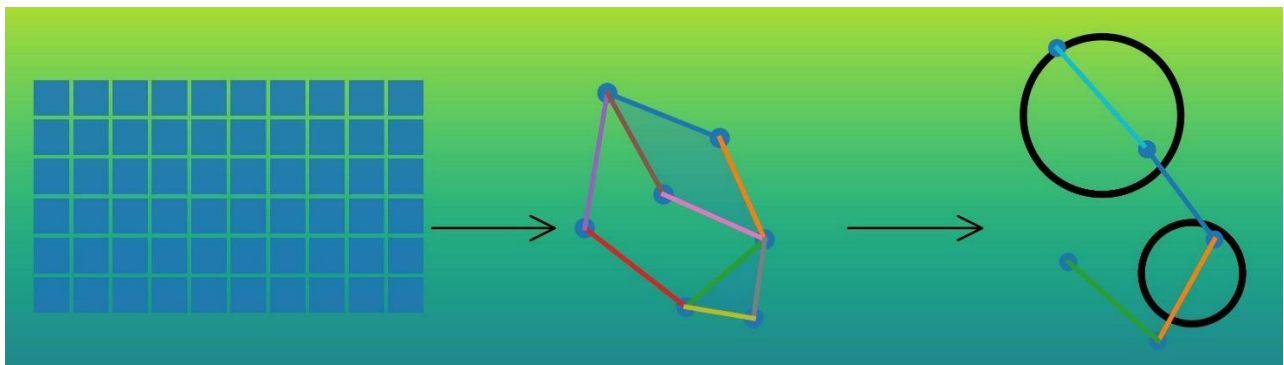
This study applies Fubini–Study geometry on projective spaces to quantify representation drift in high-dimensional data, treating states as projective vectors and measuring their evolution through trajectories defined by the Fubini–Study metric.

Graphical abstract: projective geometry separates intrinsic drift from gauge artifacts



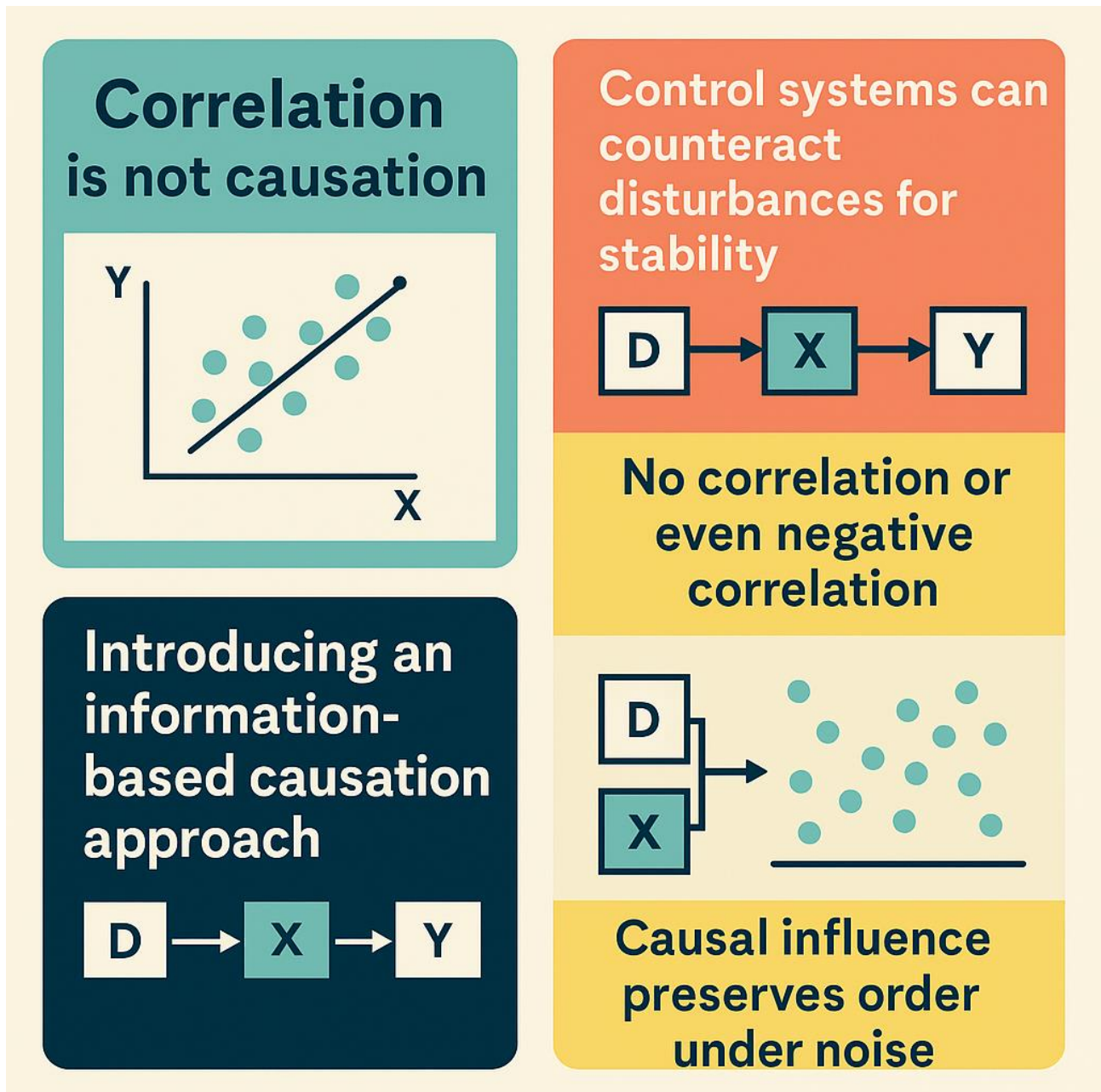
Tozzi A. 2026. Differential topological analysis of Wolfram’s Elementary Cellular Automata, Glob. J. Mob. Commun. Compute. Techno,2(1), 01-08.

This study applies algebraic topology and differential-topological analysis to Wolfram’s cellular automata, using Betti numbers, Euler characteristics, persistent homology and topological invariants to classify automaton dynamics and distinguish computational complexity classes.



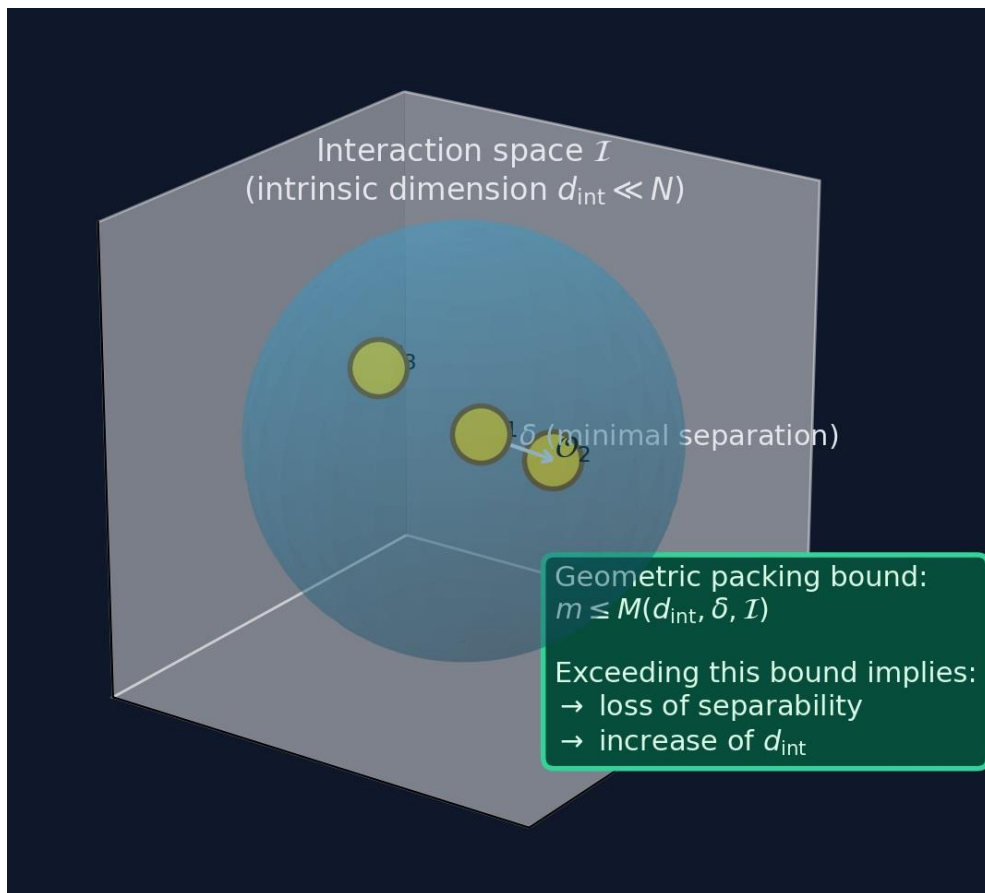
Tozzi A. 2025. Fiber Bundle Learning: A Topological Framework for Classification Using Homology and Discrete Connections. Preprints. <https://doi.org/10.20944/preprints202511.2221.v1>.
 This study introduces fiber bundle topology with homology and discrete connections for machine learning, modeling data classes as fibers over a base space and using topological invariants to guide classification.

Tozzi, A. 2025. Beyond Correlation: Redefining Causation Through Robustness and Resilience to Perturbation. Preprints. <https://doi.org/10.20944/preprints202511.0510.v1>.
 This study applies information theory and control-system dynamics, defining causation through uncertainty reduction and conditional entropy under perturbation, showing that stabilizing feedback can produce strong causal influence even when correlations vanish.



Tozzi A. 2026. Low-Dimensional Interaction Spaces Impose Geometric Constraints On Collective Organization. arXiv:2601.11592.

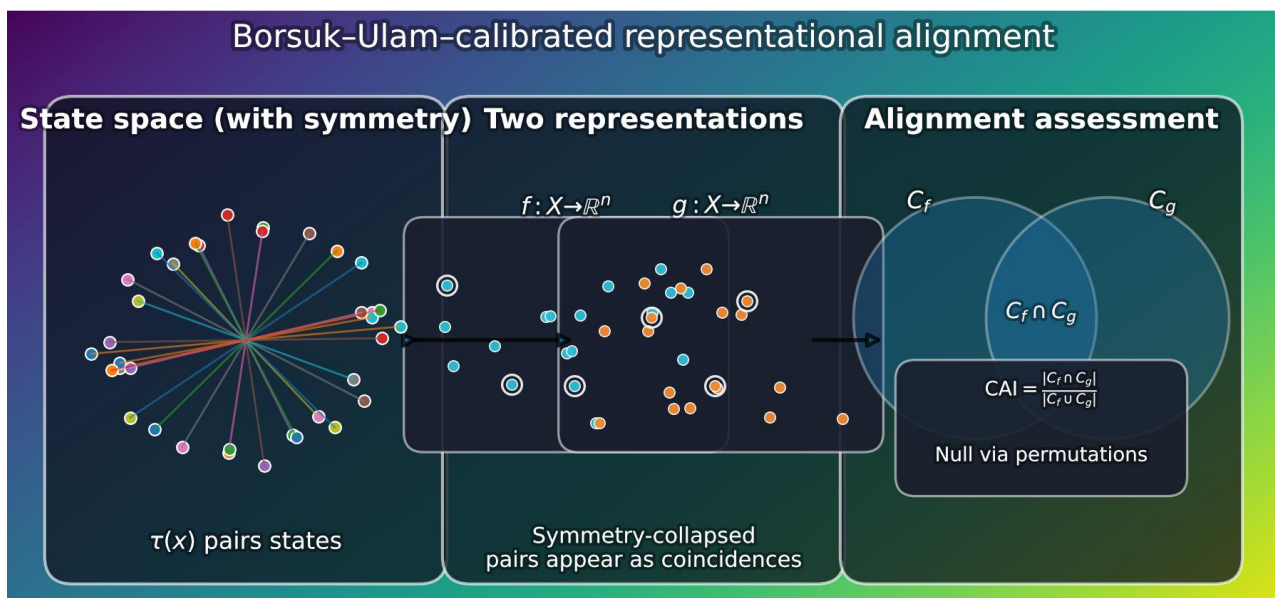
This study introduces a geometric framework based on low-dimensional interaction manifolds, showing that when effective interactions compress into a low-dimensional metric space, geometric constraints bound the diversity and separability of collective organizations.



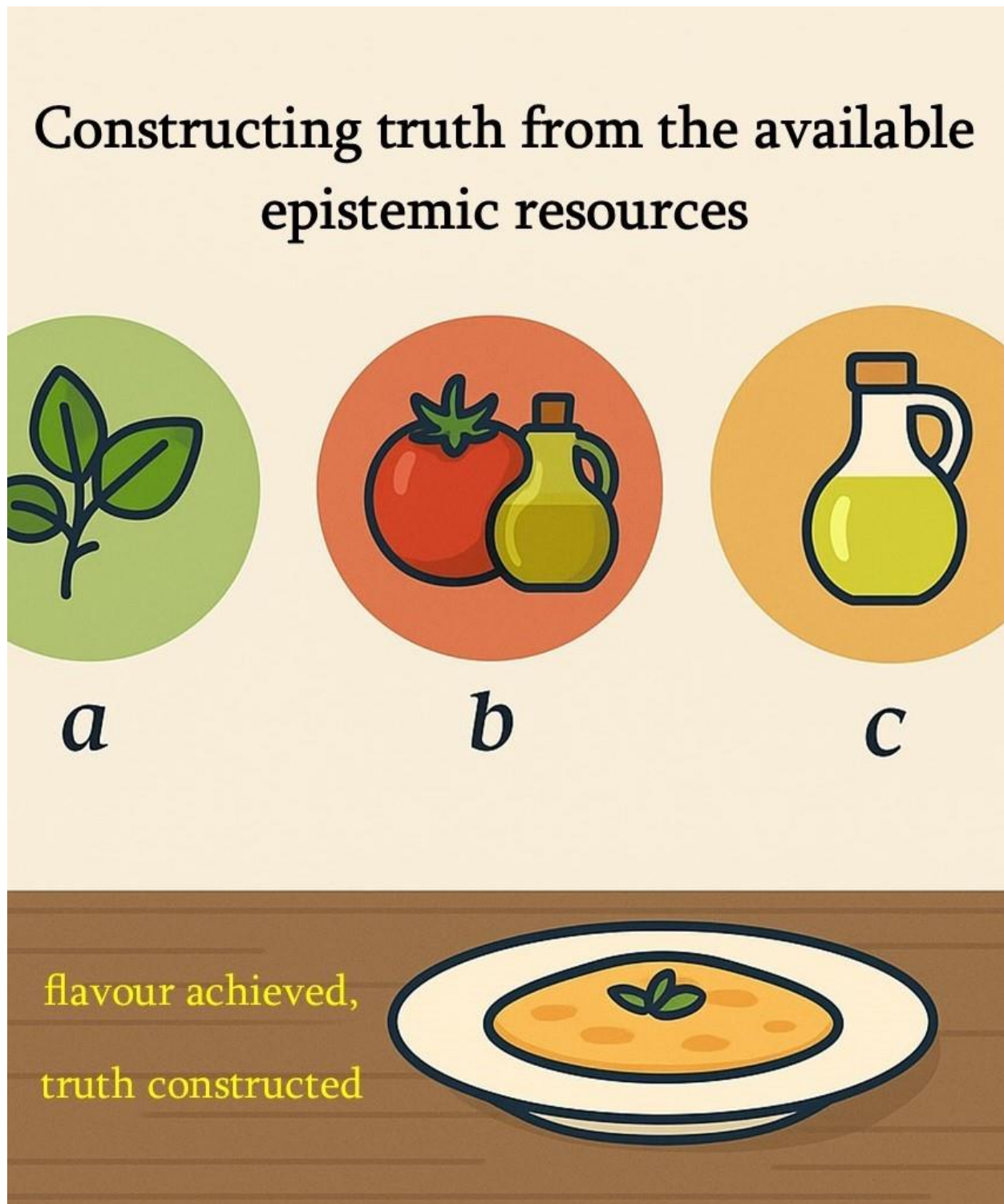
Tozzi A. 2026. A Borsuk–Ulam Argument for Representational Alignment. Preprints.

<https://doi.org/10.20944/preprints202601.1018.v1> -----

This study applies the **Borsuk–Ulam theorem** to representation spaces, showing that symmetric state spaces necessarily contain pairs of opposite states mapped to identical representations, implying unavoidable alignment constraints.



This study models scientific knowledge using resource-constrained optimization, treating theories as points in a hypothesis space and showing how limited epistemic resources restrict exploration to a feasible region of knowable truths.



CONCLUSIONS

The unpublished studies summarized here illustrate our methodological strategy: applying mathematical frameworks to biological, physical and cognitive systems in order to identify structural constraints, invariants and organizing principles that shape system behavior across different domains.

When complex systems are interpreted within suitable mathematical spaces, properties such as symmetry, dimensionality, connectivity and information flow can place limits on their possible dynamics. These constraints may reveal hidden regularities, explain why certain configurations emerge while others do not, and generate quantitative predictions that can be tested empirically.

DECLARATIONS

Ethics approval and consent to participate. This research does not contain any studies with human participants or animals performed by the Author.

Consent for publication. The Author transfers all copyright ownership, in the event the work is published. The undersigned author warrants that the article is original, does not infringe on any copyright or other proprietary right of any third part, is not under consideration by another journal and has not been previously published.

Availability of data and materials. All data and materials generated or analyzed during this study are included in the manuscript. The Author had full access to all the data in the study and took responsibility for the integrity of the data and the accuracy of the data analysis.

Competing interests. The Author does not have any known or potential conflict of interest including any financial, personal or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence or be perceived to influence their work.

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Authors' contributions. The Author performed: study concept and design, acquisition of data, analysis and interpretation of data, drafting of the manuscript, critical revision of the manuscript for important intellectual content, statistical analysis, obtained funding, administrative, technical and material support, study supervision.

Declaration of generative AI and AI-assisted technologies in the writing process. During the preparation of this work, the author used ChatGPT 5.2 to assist with data analysis and manuscript drafting and to improve spelling, grammar and general editing. After using this tool, the author reviewed and edited the content as needed, taking full responsibility for the content of the publication.

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