# Fractal Context Dynamics

*A Context-Dependent Framework for the Emergence of Physical Law*

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For more than three centuries physics has searched for universal laws. This paper inverts that premise: the laws of nature are not fundamental but are stable patterns arising within a context, and that context is the vacuum itself. We propose Fractal Context Dynamics (FCD), in which the fundamental object is a self-rewriting topological network of knots, braids, and loops, fractally organized — windings made of windings — at every scale. Spacetime, time, gravity, and matter emerge as statistical or topological properties of this network, and the familiar laws appear as renormalization fixed points: the end product of physics rather than its beginning. The framework is stated in five axioms, of which the context principle — physical "constants" are state functions of the local vacuum — marks the departure from existing emergent-spacetime programmes. Two lines of development are reported. First, a quantitative benchmark: a residual variation of the fine-structure constant with local vacuum tension, $\Delta\alpha/\alpha = \beta\cdot\Delta\chi$, predicting $\Delta\alpha/\alpha \approx 3.4\times10^{-8}$ in the photosphere of the white dwarf G191-B2B for the benchmark $\beta = \alpha/4\pi$. Second, a first computational prototype of the rewrite dynamics, which yields two instructive negative results: unconstrained local rewriting destroys geometry, and naive cycle-based restoring terms fail — implying that a bare graph carries too little structure and that the conserved quantities of the strand/knot level are a necessary ingredient. Finally, we address the criterion problem: "dimension" is an embodied human category, and we propose structural wholeness in Christopher Alexander's sense, operationalized as network measures, as the observer-anchored but non-arbitrary fixed-point criterion.

## 1. From Laws to Context

Newton, Maxwell, Einstein, and quantum mechanics have been understood as ever deeper descriptions of a reality assumed to obey the same laws everywhere and always. That search has been extraordinarily successful, yet one fundamental question has rarely been asked: are the laws of nature truly fundamental, or are they stable patterns that arise within a particular context? This question is the starting point of the present framework. Not the laws are central, but the context from which they emerge — and that context, we argue, is the vacuum itself. The vacuum is not a background in which physics takes place; the vacuum is the physics.

## 2. Background

Three independent results motivate this inversion. Sakharov showed that gravitation can arise from vacuum fluctuations, as an elasticity of the vacuum. Volovik describes the vacuum as a quantum liquid in which Lorentz invariance is merely a low-energy property. Jacobson derived the Einstein equations from thermodynamics, with spacetime appearing as an equation of state rather than a fundamental object. A fourth line supplies the missing process-ontology: Spencer-Brown begins not with matter or space but with a single primitive act, the drawing of a distinction, and

Kauffman showed that a distinction which re-distinguishes itself produces stable forms (eigenforms). Taken together, these results suggest that neither particles, nor fields, nor even spacetime are fundamental: fundamental is a recursive process that continually rewrites itself.

## 3. Axioms

A1 — Primitive. The only primitive is the local rewrite step $T \to R(T)$, where T is a dynamic topological complex (knots, braids, loops) and R contains only local topological transformations. At this level neither space nor time exists; there is only topological evolution.

A2 — Criticality. The rewrite rules drive the complex toward critical self-organization. Under coarse-graining, R flows to universal fixed points — and those fixed points are the familiar laws of nature.

A3 — Fractality. The fixed-point structure is scale-invariant: every winding is built of windings. The effective dimension is scale-dependent, approximately 2 at the Planck scale and approaching 4 macroscopically, consistent with the spectral-dimension results of Causal Dynamical Triangulations.

A4 — Context principle. The effective laws and "constants" at scale s are state functions of the local vacuum: $L(s) = \Phi(T \mid s)$. Constants are elastic moduli of the vacuum, not universals. This axiom marks the departure from existing emergence programmes (Jacobson, CDT, Wolfram/Gorard, loop quantum gravity), which keep the constants universal.

A5 — Invariance principle. All physical quantities are either topological invariants of stable configurations (charge, spin, particle identity) or statistical quantities of the ensemble (metric, temperature, time).

## 4. Emergence

Geometry. The metric is not postulated; it arises as the correlation structure of the network, $g = F(T)$. Space is a collective state of the vacuum, not an object.

Time. The fundamental dynamics consists only of successive rewritings. Physical time appears when a statistical state is formed, in line with the thermal time hypothesis of Connes and Rovelli: time is an ordering generated by the state itself, not a substance.

Gravity. The information content of the network determines its entropy; a local change of the network changes the entropy, and via $\delta Q = T\, dS$ the Einstein field equations follow as a macroscopic equation of state. Gravity is thermodynamic, not a fundamental interaction, and the “curvature” of spacetime can be reread as a refractive-index profile of the vacuum.

Matter. Elementary particles are stable topological configurations of the network. Mass, spin, and charge are not imposed but arise as topological invariants: matter is frozen topology.

## 5. A Quantitative Benchmark: Context-Dependence of α

To show how axiom A4 becomes testable, we develop one worked example. Define the local vacuum tension dimensionlessly as $\chi = |\Phi|/c^2$, and adopt, following the polarizable-vacuum representation of Dicke and Puthoff, the ansatz $\varepsilon(\chi) = K\cdot\varepsilon_0$ and $\mu(\chi) = K\cdot\mu_0$ with $K = e^{(2\chi)}$, hence $c_{local} = c/K$. To first order this reproduces the classical tests of general relativity (light bending, gravitational redshift, Shapiro delay) without curved spacetime.

In Dicke’s construction the accompanying variations of e and ħ are tuned such that the fine-structure constant $\alpha = e^2/4\pi\varepsilon_0\hbar c$ remains exactly invariant. Under axiom A4 that tuning is exact only at the renormalization fixed point; the fractal structure of the vacuum leaves a residue, $\Delta\alpha/\alpha = \beta\cdot\Delta\chi$. Current spectroscopy of the hot white dwarf G191-B2B ($\chi \approx 6\times10^{-5}$) gives $\Delta\alpha/\alpha = (0.007 \pm 0.087)\times10^{-6}$, and Gaia-DR3 mass–radius analyses reach $|\Delta\alpha/\alpha| \sim 10^{-7}$; it follows that $\beta \leq {\sim}1.5\times10^{-3}$.

As a benchmark we take $\beta = \alpha/4\pi \approx 5.8\times10^{-4}$, the one-loop vacuum-polarization factor — a heuristic choice, motivated by the expectation that the residue is generated by vacuum polarization, but not derived from the rewrite dynamics. It yields the prediction $\Delta\alpha/\alpha \approx 3.4\times10^{-8}$ at G191-B2B, just below the current bound and decidable at the next improvement in spectroscopic precision. Neutron-star photospheres ($\chi \approx 0.2$) would show $\Delta\alpha/\alpha \sim 10^{-4}$, an unmistakable signal.

Two outcomes are forbidden. First, the detection of a quantized spin-2 graviton falsifies the framework, since gravity is here thermodynamic. Second, a gravitationally explained Webb dipole is excluded: the reported $\Delta\alpha/\alpha \sim 10^{-5}$ would require $\Delta\chi \sim 10^{-2}$, far larger than realistic potential differences. FCD therefore predicts that the dipole, if real, reflects cosmic evolution of the mean vacuum tension — the vacuum relaxing with expansion — or observational systematics.

## 6. Explicit Rewrite Dynamics: A Prototype and Two Negative Results

A first computational prototype of the rewrite dynamics has been implemented (Python, ~150 lines; code available with this paper). The state is a 4-regular graph of 3,600 nodes, initialized as a two-dimensional periodic lattice representing a locally two-dimensional vacuum. The rewrite rule R consists of degree-preserving local double-edge swaps, with a tunable rate of non-local swaps, optionally filtered by a Metropolis acceptance step on a local cycle-based action. The probe is observer-free: the return probability of a random walk on the network, from which a spectral dimension D_s(t) can be extracted as a function of diffusion time (scale). The estimator is validated on the pure lattice, where it correctly yields D_s ≈ 2.

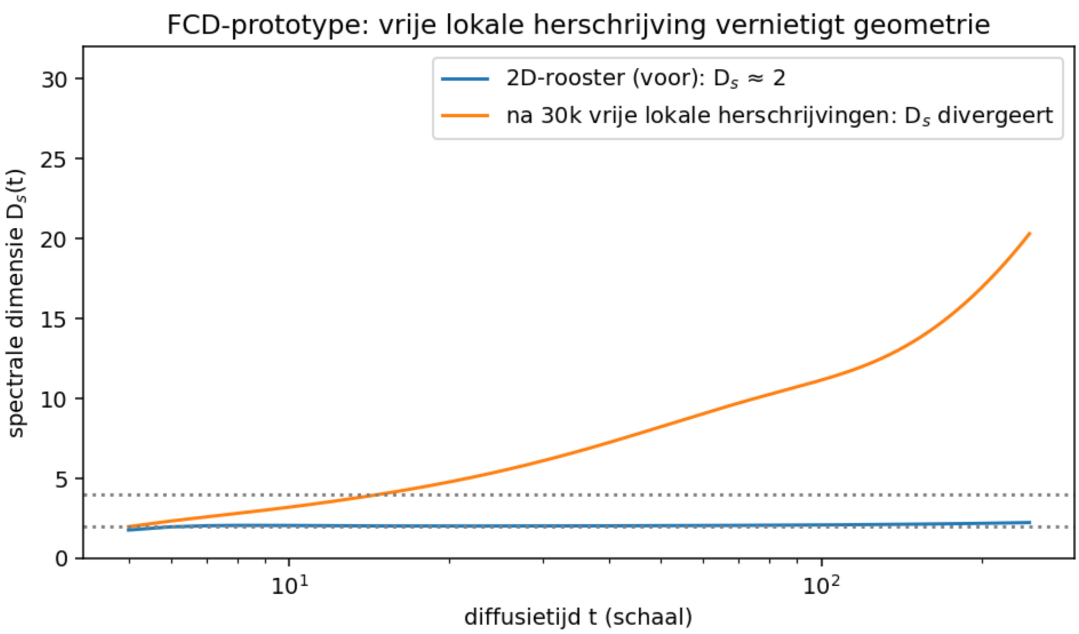


*Figure 1. Spectral dimension D_s(t) before and after 30,000 unconstrained local rewrite steps. The initial lattice measures D_s ≈ 2; the rewritten network is an expander whose apparent dimension diverges.*

Two negative results follow. First, unconstrained local rewriting destroys geometry: after 30,000 local swaps the lattice has become an expander graph and the measured dimension diverges (Figure 1). Criticality (axiom A2) therefore does not come for free from locality; without a restoring principle, the only fixed point of local rewriting is total disorder. Second, naive restoring terms fail: a triangle-based action has no gradient on a sparse network (there are no triangles to steer on), while a square-based action actively rewards chord formation — 94% of proposed moves are energetically favourable on a fresh lattice — and densifies the network instead of ordering it.

The implication is the substantive finding of the prototype: a bare graph carries too little structure to stabilize geometry. Causal Dynamical Triangulations solves this by imposing causal structure externally. The FCD-native solution is that the strand level supplies it internally: crossings carry orientation and sign, and hence conserved quantities — winding number, writhe — that a bare graph lacks. On this reading the strand/knot structure is not a decorative choice of representation but the necessary ingredient that prevents the flow to disorder. Upgrading the prototype's state from graph to oriented strand diagram with conserved winding number is the identified next step.

## 7. The Criterion Problem: Dimension, Embodiment, and Wholeness

The prototype used "$D_s \to 4$" as its success criterion. This imports an anthropic assumption. As Poincaré argued, the three-dimensionality of space is a property of the sensorimotor apparatus — the group of bodily compensations by which perception is corrected — rather than of the world an sich; Kant placed space among the forms of intuition; and Lakoff and Johnson showed that abstract categories, dimension included, are grounded in bodily schemata. The return probability of a random walk is an observer-free statistic of the network, but calling its exponent "dimension" and demanding the value 4 is a statement about the interface between the vacuum and embodied observers, not about the vacuum itself. Instruments without bodies register behaviour consistent with 3+1; what is embodied is the category and the target value, not the underlying relational stability.

This reframes the prototype's first negative result: the dynamics alone does not produce space, and if space nevertheless appears, something selects it. We therefore replace the anthropocentric target with an observer-anchored but non-arbitrary criterion: structural wholeness in Christopher Alexander's sense. Alexander showed empirically (the mirror-of-the-self test) that judgements of harmony are highly consistent across persons, and structurally that "living" configurations share identifiable properties — levels of scale, strong centers, boundaries, alternating repetition, local symmetries, echoes, not-separateness — several of which have been mathematized by Salingaros. These properties translate directly into the present framework: levels of scale is fractality (axiom A3); strong centers are stable knots — Kauffman's eigenforms, centers reinforcing centers as knots stabilizing knots; echoes are self-similarity. The disordered expander of Section 6 scores zero on all of them; a living structure scores high. The fixed-point criterion for R thus becomes: does the dynamics produce structure that is whole in Alexander's operationalizable sense — with "3+1 dimensions" reinterpreted as a statement about how embodied observers read that wholeness, not as a property the vacuum must deliver by itself.

## 8. Further Tests

- Dimensional dispersion: as the effective dimension runs toward 2 at small scales, high-energy photons from gamma-ray bursts should show energy-dependent arrival times.
- Particle spectrum as knot spectrum: mass ratios should follow from a topological complexity measure on knot classes. The Bronze Mean sequence (1, 1, 4, 13, 43, 142; $T(n) = 3T(n-1) + T(n-2)$) is proposed as the candidate ordering of winding levels.
- Low-acceleration regime: near the relaxed ground state of the vacuum the dynamics should deviate from Newton — MOND-like behaviour as a phase transition of the vacuum rather than dark matter.

## 9. Open Problems and Research Programme

The prototype of Section 6 supplies a candidate form for the rewrite rules R and a reproducible algorithm, but leaves the central elements open: (i) the conserved strand-level structure (orientation, winding number, writhe) must be built into the state, since Section 6 shows a bare graph cannot hold geometry; (ii) the quantitative nature of vacuum tension — scalar, tensorial, or a phase variable of the winding structure; (iii) the functional dependence of $\varepsilon_0$ on it; (iv) the mechanism that produces and discharges the tension, including whether mass is the source of tension or itself frozen tension; and (v) the recurrence relation between successive winding levels, for which the Bronze Mean recursion is the working candidate. On the criterion side, two or three of Alexander's wholeness properties (levels of scale, strong centers, echoes) are to be operationalized as network measures and installed as the fixed-point test in place of the spectral dimension. Beyond these, the derivation of quantum amplitudes remains open, for which Rowlands' nilpotent rewrite system is the natural route, as does the status of the observer — who draws the first distinction — which decides whether the framework is participatory in Wheeler's sense or classically falsifiable.

## Limitations

FCD is presented as a research programme, not as established physics. Sections 1–4 reinterpret existing results within a single ontology and add no new mathematics. The quantitative layer of Section 5 rests on a borrowed ansatz and a heuristic benchmark for β, chosen for physical plausibility rather than derived from the axioms. The prototype of Section 6 is a day-one implementation: its negative results are informative but obtained on one family of graphs, one move set, and modest sizes, and loop creation/annihilation is not yet implemented. The wholeness criterion of Section 7 is proposed, not yet operationalized. The observational bounds cited are current as of mid-2026 and the Hu et al. reference data should be verified against the primary publications.

## Annotated References

Spencer-Brown, G. (1969). Laws of Form. Allen & Unwin.

*Supplies the primitive of the entire framework: the act of distinction as the origin of form, prior to space, time, and matter.*

Kauffman, L. H. (1987). "Self-reference and recursive forms." Journal of Social and Biological Structures 10(1), 53–72; and Kauffman's knot-logic papers.

*Shows that self-applied distinction stabilizes into eigenforms, and connects distinction to knot and braid topology. In Section 7, eigenforms reappear as Alexander's strong centers: knots stabilizing knots.*

Sakharov, A. D. (1967). "Vacuum quantum fluctuations in curved space and the theory of gravitation." Doklady Akademii Nauk SSSR 177, 70–71.

*Induced gravity: gravitation as an elasticity of the vacuum rather than a fundamental force. The organizing idea behind vacuum tension χ.*

Volovik, G. E. (2003). The Universe in a Helium Droplet. Oxford University Press.

*Demonstrates in condensed-matter analogues that Lorentz invariance, "particles", and effective metrics emerge in the low-energy limit of a quantum liquid — the strongest existing precedent for context-dependent laws (axiom A4).*

Jacobson, T. (1995). "Thermodynamics of spacetime: the Einstein equation of state." Physical Review Letters 75, 1260–1263.

*Derives the Einstein field equations from δQ = T dS on local horizons. FCD adopts this route for the emergence of gravity and adds the forbidden outcome: no graviton.*

Connes, A., & Rovelli, C. (1994). "Von Neumann algebra automorphisms and time-thermodynamics relation in generally covariant quantum theories." Classical and Quantum Gravity 11, 2899–2917.

*The thermal time hypothesis: physical time is generated by the statistical state itself. FCD's account of time as ordering, not substance, rests on this result.*

Ambjørn, J., Jurkiewicz, J., & Loll, R. (2005). "Spectral dimension of the universe." Physical Review Letters 95, 171301.

*Causal Dynamical Triangulations: the spectral dimension runs from ≈4 at large scales to ≈2 near the Planck scale. Also the model case of an externally imposed restoring principle (causal structure), against which Section 6 contrasts the strand-internal alternative.*

Dicke, R. H. (1957). "Gravitation without a principle of equivalence." Reviews of Modern Physics 29, 363–376; Puthoff, H. E. (2002). "Polarizable-vacuum (PV) approach to general relativity." Foundations of Physics 32, 927–943.

*The polarizable-vacuum representation of gravity: ε and μ as functions of gravitational potential, curvature as a refractive-index profile. The direct template for the equation of state in Section 5 — and the tuning that FCD breaks.*

Robinson, V. N. E. Sub-quantum gravity model (Qeios / QuiCycle publications).

*Proposes gravity as arising from rotating-photon nucleons altering the electric permittivity of space. Non-mainstream; included as a third reference point alongside Sakharov and Volovik, not as established physics.*

Williamson, J. G., & van der Mark, M. B. (1997). "Is the electron a photon with toroidal topology?" Annales de la Fondation Louis de Broglie 22(2), 133–160.

*The electron as a self-confined photon with toroidal topology — the concrete model behind "matter as frozen topology" and the knot-spectrum test.*

Rowlands, P. (2007). Zero to Infinity: The Foundations of Physics. World Scientific.

*The nilpotent Universal Rewrite System: the candidate route for deriving quantum amplitudes within the open core of Section 9, and an independent precedent for rewrite-based physics.*

Poincaré, H. (1902). La Science et l'Hypothèse. Paris: Flammarion.

*Argues that the three-dimensionality of space derives from the group of bodily displacements and compensations — the classical source for Section 7's claim that dimension is an embodied category.*

Lakoff, G., & Johnson, M. (1999). Philosophy in the Flesh. New York: Basic Books.

*Embodied cognition: abstract categories are grounded in sensorimotor schemata. Grounds the reinterpretation of "3+1 dimensions" as a statement about the observer–vacuum interface.*

Alexander, C. (1977). A Pattern Language. New York: Oxford University Press; Alexander, C. (2002–2005). The Nature of Order, Books 1–4. Berkeley: Center for Environmental Structure.

*Structural wholeness and its fifteen properties, with the empirical mirror-of-the-self test showing harmony judgements are inter-subjectively stable. Supplies the observer-anchored, non-arbitrary fixed-point criterion of*

*Section 7; Book 4 (The Luminous Ground) extends the theory to cosmology.*

Salingaros, N. A., & Mehaffy, M. W. (2011). Principles of Urban Structure. Amsterdam: Techne Press.

*Mathematizes several of Alexander's wholeness properties via complexity and network theory — the starting point for operationalizing wholeness as network measures on T.*

Webb, J. K., et al. (2011). "Indications of a spatial variation of the fine structure constant." Physical Review Letters 107, 191101.

*The reported $\Delta\alpha/\alpha$ dipole at the $10^{-5}$–$10^{-6}$ level from quasar absorption spectra. FCD predicts this dipole cannot be gravitational in origin — one of the framework's forbidden outcomes.*

Berengut, J. C., et al. (2013). "Limits on the dependence of the fine-structure constant on gravitational potential from white-dwarf spectra." Physical Review Letters 111, 010801.

*Establishes hot white dwarfs (Fe V / Ni V lines in G191-B2B) as probes of α in strong gravitational potentials — the experimental arena for the central prediction of Section 5.*

Hu, J., et al. (2019–2021). White-dwarf α-variation analyses, including $\Delta\alpha/\alpha = (0.007 \pm 0.087)\times10^{-6}$ for G191-B2B, and continuum-placement systematics studies (MNRAS).

*The sharpest current spectroscopic bound used in Section 5, giving $\beta \leq \sim1.5\times10^{-3}$. Bibliographic details to be verified against the primary publications.*

Uniyal, A., Kalita, S., Mizuno, Y., Chakrabarti, S., & Lu, Y. (2025). "Refining fundamental constants with white dwarfs." Monthly Notices of the Royal Astronomical Society 542, 3395–3401.

*Gaia-DR3 mass–radius constraints reaching $|\Delta\alpha/\alpha| \sim 10^{-7}$ — the level at which the benchmark prediction of $3.4\times10^{-8}$ becomes decidable*