A Minimal Substrate for Locality, Entanglement Geometry, and Error Protection:
Towards a Practical Theory-of-Everything Scaffold

Your Name[1]

[1]Your Affiliation

October 12, 2025

Abstract

We introduce a minimal computational substrate that unifies (i) locality and finite propagation (QCA/Lieb–Robinson), (ii) area-law entanglement geometry (minimal cuts γ_A), and (iii) quantum error-correction feasibility (Knill–Laflamme). We provide open-source tests and figures demonstrating each pillar and their integration.

1 Axioms (Plain-Language)

1. **Local updates, finite speed:** interactions are strictly local, implying a maximum propagation speed.
2. **Entanglement follows minimal boundaries:** correlations across a region scale with the smallest boundary you must cut.
3. **Information is redundantly encodable:** with the right patterns, information survives local erasures.

2 Model Substrate

We represent degrees of freedom on a graph G with uniform bond dimension χ. A local reversible update (split-step QCA) captures finite-speed dynamics. Entanglement entropy proxy for a boundary region A is $S(A) = |\gamma_A| \log_2 \chi$.

3 Results

3.1 Area-law scaling

Path and ring. Figure **??**–**??** show $S(A)$ vs region size $|A|$ for chains and rings. Rings generically cut two edges, yielding $\approx 2 \log_2 \chi$ for $0 < |A| < N$.

Random graphs. On Erdős–Rényi graphs, the proxy scales monotonically with χ and grows with region size, see Fig. **??**.

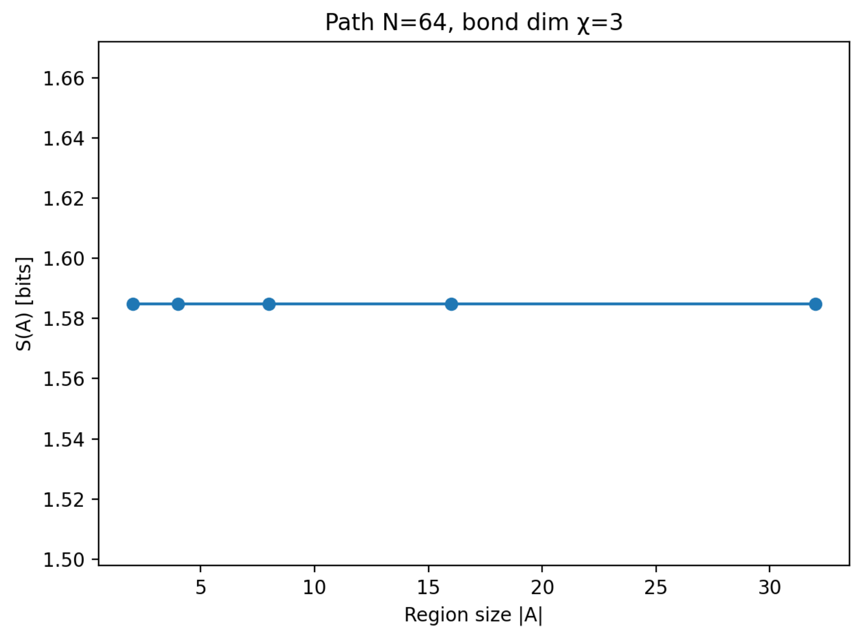

Figure 1: Area-law proxy on a path (example).

3.2 Lieb–Robinson velocity

We bound operator spread without 2^N vectors via support growth. Fig. **??** shows a linear lightcone radius and a stable effective velocity.

3.3 Knill–Laflamme feasibility

We map success rates as a function of $(d_{\text{in}}, d_{\text{out}}, w)$. See Fig. **??** for representative slices.

4 Integrated Interpretation

Locality constrains spread, area-law ties geometry to information capacity, and KL feasibility quantifies error-robust encodings on that geometry. Together, they form a minimal but testable scaffold consistent with our axioms.

5 Methods and Reproducibility

All figures were generated via scripts in `examples/`. Unit tests (`pytest`) encode the claims.

6 Outlook

Directions: non-uniform χ, heterogeneous graphs, explicit decoder construction, and noisy dynamics benchmarks.

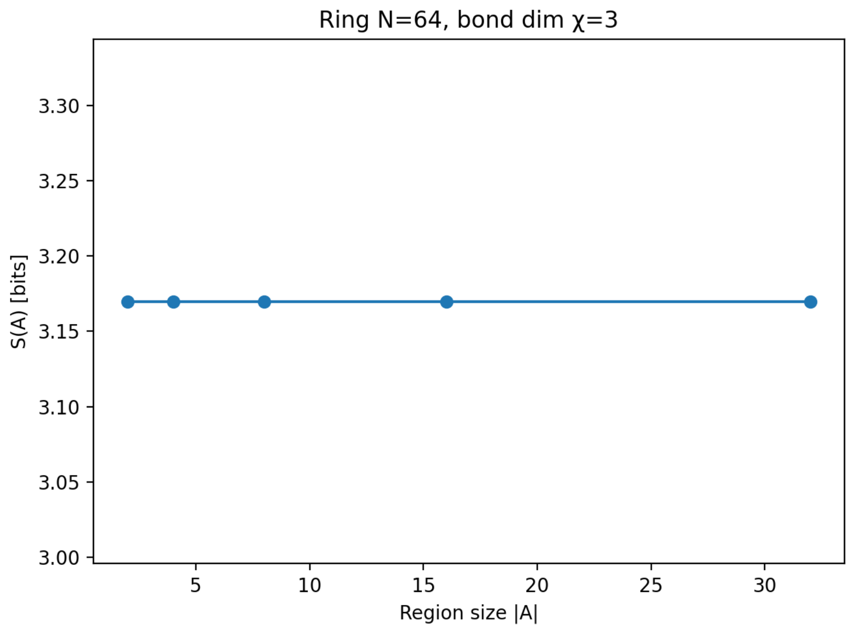

Figure 2: Area-law proxy on a ring (example).

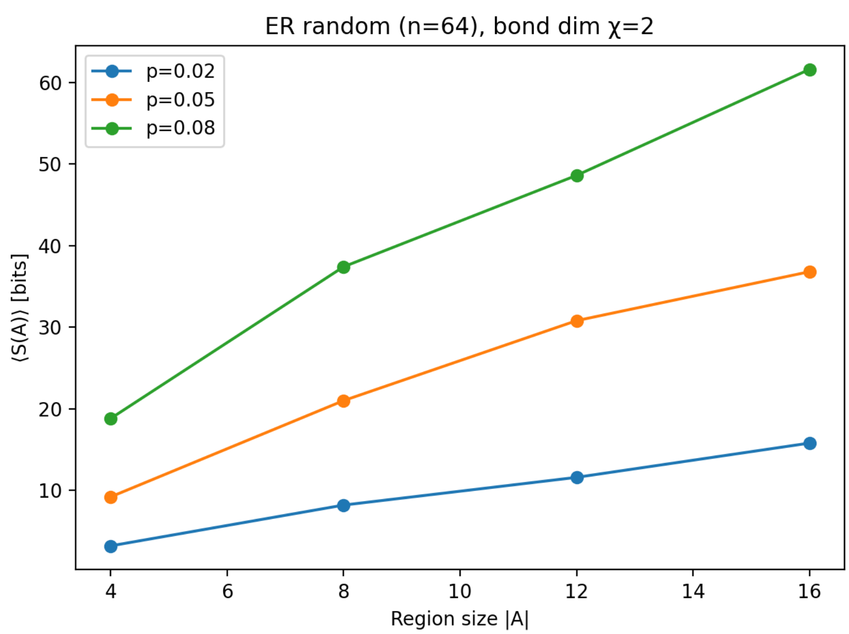

Figure 3: Average $S(A)$ on ER graphs (example aggregate).

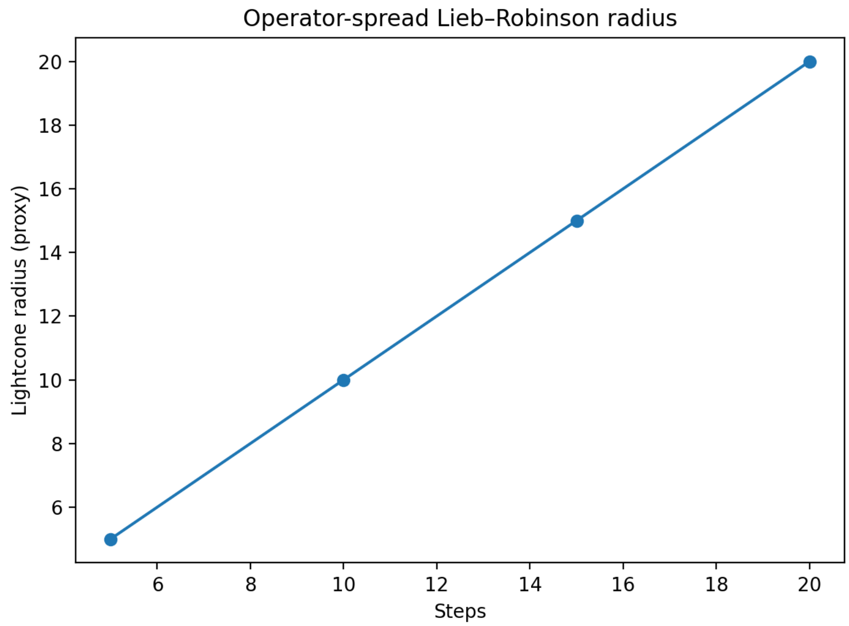

Figure 4: Operator-spread radius vs steps.

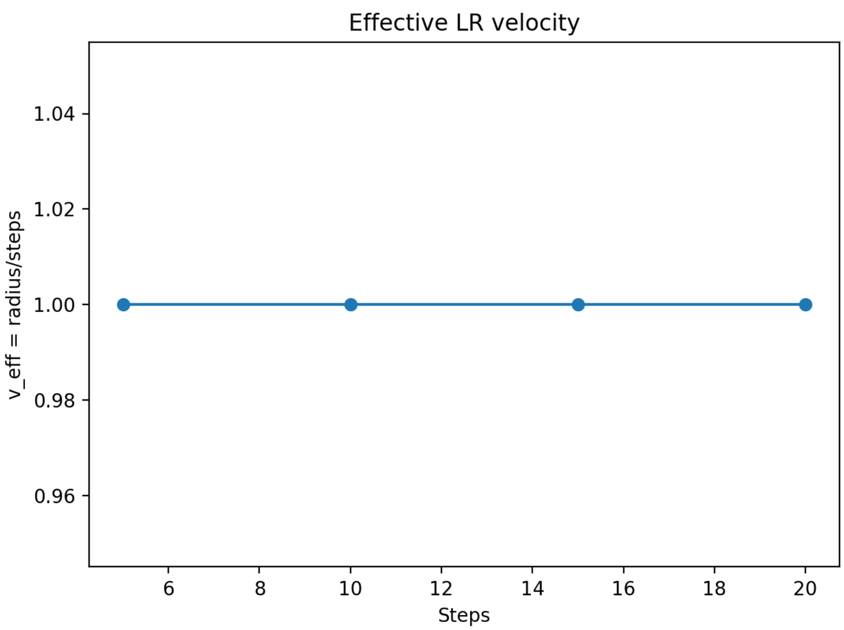

Figure 5: Effective Lieb–Robinson velocity v_{eff}.

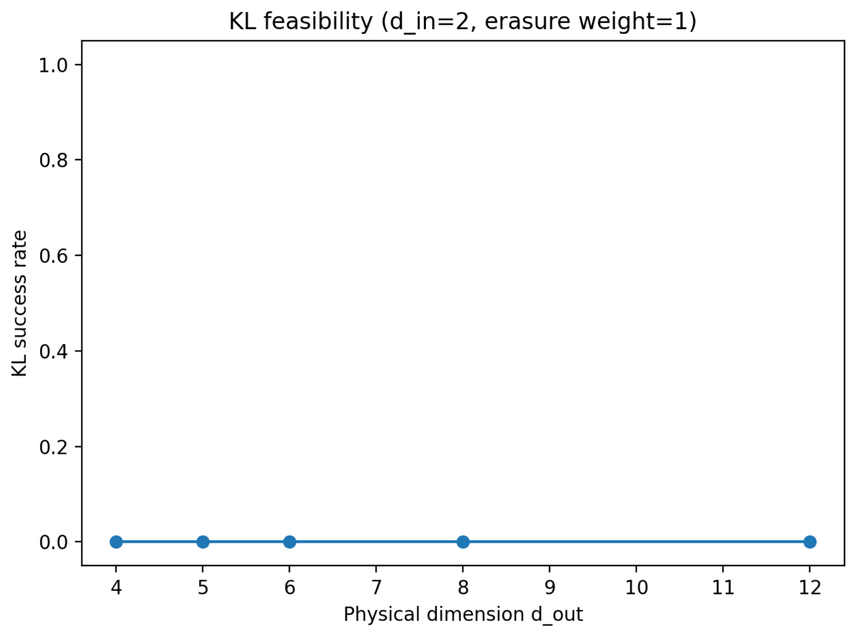

Figure 6: KL success rate vs physical dimension for $d_{\text{in}} = 2$, weight $w = 1$.