geDIG: A One-Gauge Framework for Controlling Dynamic Knowledge Graphs

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Abstract

We propose geDIG, a single-gauge ($\mathcal{F}$) control framework for dynamic knowledge graphs that unifies structure cost (normalized edit path cost, ΔEPC) and information gain (entropy decrease and path shortening, ΔIG). The two-stage gating (AG: attention, DG: decision) drives acceptance/rejection/exploration/backtrack/eviction in an event-driven manner. The design cleanly separates 0-hop novelty/error detection (FEP-side) from multi-hop compression/shortcuts (MDL-side), achieving practical anytime operation. We present results-first summaries for four experiments: (I) PoC on partial-observation mazes, (II) static RAG baselines (flat vs GraphRAG/GNN vs Graph Transformer vs geDIG-soft), (III) dynamic GRAG with PSZ (Perfect Scaling Zone), and (IV) insight-vector alignment. Finally, we formulate an operational FEP–MDL bridge and provide a thermodynamic reading (free energy) of $\mathcal{F}$.

1 Introduction

We study when and how to accept, connect, and reuse new knowledge episodes in a dynamic knowledge graph (KG). Our core hypothesis: a single numerical gauge $\mathcal{F}$ can reliably drive both learning (curation) and inference (retrieval/use).

One-Gauge and Two-Stage Gates We define

$$\mathcal{F} = \Delta\mathrm{EPC}_{\mathrm{norm}} - \lambda\,\Delta\mathrm{IG}_{\mathrm{norm}}, \quad \Delta\mathrm{IG}_{\mathrm{norm}} = \Delta H_{\mathrm{norm}} + \gamma\,\Delta\mathrm{SP}_{\mathrm{rel}}, \tag{1}$$

where λ sets the information temperature and γ balances entropy vs path-efficiency. AG (attention) triggers on high 0-hop novelty/error; DG (decision) commits only when multi-hop gain is confirmed (shortcuts/compression).

Contributions (short)

- Results-first, unified control: $\mathcal{F}$ and two-stage gates for online acceptance/search/eviction.
- Static and dynamic RAG: clean split; dynamic metrics (PSZ, FMR) isolated in the Dynamic chapter.
- Operational FEP–MDL bridge and a free-energy reading of $\mathcal{F}$ (engineering, not identity).

2 Design: One Gauge and Two-Stage Gating

2.1 0-hop vs Multi-hop: FEP and MDL

0-hop evaluates draft wiring at the query hub (novelty/error; FEP-side), while multi-hop evaluates shortcuts/compression on induced subgraphs (MDL-side). Let $g_0 = \Delta\mathrm{EPC}_{\mathrm{norm}} - \lambda\,\Delta H_{\mathrm{norm}}$ and $g_{\min} = \min_h\{\Delta\mathrm{EPC}_{\mathrm{norm}} - \lambda(\Delta H_{\mathrm{norm}} + \gamma\,\Delta\mathrm{SP}^{(h)}_{\mathrm{rel}})\}$. AG fires if $g_0 > \theta_{\mathrm{AG}}$; DG fires if $\min\{g_0, g_{\min}\} \leq \theta_{\mathrm{DG}}$.

2.2 Thermodynamic Reading (Metaphor)

We can read $\mathcal{F}$ as an operational free energy:

$$U := \Delta\mathrm{EPC}_{\mathrm{norm}} - \lambda\,\gamma\,\Delta\mathrm{SP}_{\mathrm{rel}}, \quad S := \Delta H_{\mathrm{norm}}, \quad F := U - \lambda S, \tag{2}$$

so $\mathcal{F}$ is isomorphic to F by term rearrangement. The coefficient λ plays the role of information temperature.

3 Experiment I: Maze PoC (results-first)

Summary geDIG achieves large reductions in exploration ratio and revisit rate, with short backtracks and near-immediate dead-end detection. Example (25×25): **[TBD: exploration 0.38, revisit 1.28, backtrack 4.3, detection 0.8, success 100%]**.

Metrics Primary: exploration ratio (unique/total), revisit (steps/unique), avg backtrack (AG→DG), dead-end detection delay, success rate. Secondary: Regret, SPL.

Success Criteria Necessary: success $\geq$ 95%, AG 5–10%, DG 2–5%, DG/AG 30–50%, threshold stability (train/val within 2%). Sufficient: exploration $\leq$ 0.40, revisit $\leq$ 1.5, backtrack $\leq$ 5, detection $\leq$ 1 with significance vs Greedy Novelty (Welch+Bonferroni, $p<0.01$, $d>0.5$). Diagnostic: Regret median $\leq +5$, SPL mean ≥ 0.85.

Baselines (same conditions) Greedy Novelty, ε-greedy, UCB1-like, Partially-Observed A*, and ablations (EPC-only / IG-only / no AG/DG / 0-hop only). Dijkstra/A* used as upper-bound diagnostics.

4 Experiment II: RAG Baselines (static only)

Summary Under equal-resources, geDIG-soft (G1) improves EM/F1 by **[TBD: +2–5pt]** over GT-RAG (B2), increases citation/path faithfulness by **[TBD: +5–10pt]**, with comparable P50/P95 latency.

Baselines B0: Flat RAG (SBERT, HNSW, Top-k), B1: GraphRAG (GNN), B2: Graph Transformer, G1: B2 + geDIG-soft (sigmoid $(\tau\mathcal{F})$ for weighting/pruning/ordering). Static-only here; dynamic is in Experiment III.

Dataset and Protocol 50 domains (mix of single-domain, cross-domain 2/3-hop, analogical). Sources: HotpotQA/2Wiki + curated. Equal-resources table (embedder/ANN/Top-k/LLM/temp/tokens/HW/parallelism/measurement) fixed across methods. No-peeking: train (burn-in for thresholds) / val / test split; thresholds fixed on val.

5 Experiment III: Dynamic GRAG $\times$ geDIG

Summary With geDIG-soft applied consistently to retrieval/integration/summarization (G2), Temporal Consistency improves by **[TBD: +5–10pt]**, update lag remains comparable or lower, KG contamination (FMR) decreases, and PSZ points emerge.

Dynamic Metrics Temporal Consistency, update lag (ingest→available), KG contamination rate (FMR, rolling), 0-hop rejection, AG/DG rates. PSZ: Acc $\geq 95\%$, FMR $\leq 2\%$, extra P50 $\leq$ 200ms.

Time-Series and Operating Curves Plot ΔEPC/ΔH/ ΔSP/$\mathcal{F}$ with acceptance time-series (pending→confirmed, C-value), and Operating Curves (Acc–FMR–Latency) with PSZ band.

6 Experiment IV: Insight-Vector Alignment

Summary Readout vectors from DG-confirmed subgraphs align with LLM answer embeddings: **[TBD:** Δs=+0.2x**,** p<0.0x**,** N=200]. Baselines: random, Top-k, threshold, AG-selected.

7 FEP–MDL Bridge (operational proposition)

Definition We call an operational correspondence a relation that (i) is proportional (not identical), (ii) has a bounded residual $O(1/N)$ under assumptions, and (iii) yields testable predictions. Under mild assumptions (normalization, bounded horizon, decomposable edits, stable entropy estimation), $\mathcal{F} \propto \Delta\mathrm{MDL} + O(1/N)$. The coefficient $\lambda \approx c_D/c_M$ anchors scales.

Implications A single control signal justifies simultaneous control of structure edits and inference. EPC on the structure side and IG on the information side avoid double counting. Ablations corroborate the roles of ΔH and ΔSP.

8 Conclusion

We presented geDIG, a one-gauge control framework with two-stage gates, covering PoC (maze), static RAG baselines, dynamic GRAG (PSZ), and insight alignment, and provided an operational FEP–MDL bridge (free-energy reading). Future work includes Phase 2 (offline rewiring) and large-scale evaluations.

References