A Path Already Walked: On Inheriting Network-Neuroscience Tools for Mechanistic Interpretability

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Abstract

Mechanistic interpretability is moving from neurons and heads toward circuits, dictionary features, and attribution graphs. That transition is productive, but it also raises a familiar issue. Many important phenomena are relational rather than component-local. Network neuroscience has spent two decades building graph vocabulary, null models, and failure modes for related problems. We argue for a disciplined import rather than a loose brain analogy. We specify the transformer graph contract required before the import is meaningful, give a compact mapping from network-neuroscience primitives to transformer analyses, work through a local effective-connectivity proxy for gated MLPs, and state eight testable translations with failure criteria. This is a position and methodology paper. It contributes a vocabulary, graph contracts, and falsifiable tests meant to structure future empirical work rather than report results of its own. We do not report transformer experiments, and we do not claim that neuroscience results transfer automatically.

1. Position

Mechanistic interpretability has made progress, but its explanatory units keep moving. Early work analyses individual neurons (Olah et al., 2020). Later work studies attention heads, circuits, superposition, dictionary features, and attribution graphs (Elhage et al., 2021; Wang et al., 2023; Elhage et al., 2022; Bricken et al., 2023; Templeton et al., 2024; Ameisen et al., 2025). This shift shows that part-enumeration is useful but incomplete.

Recent work makes the issue more concrete. Sparse autoencoders can be inconsistent across runs (Song et al., 2025), may not identify canonical units (Leask et al., 2025), and require falsification-oriented explanation tests (Ma et al., 2025). Circuit work is also evolving into graph work through automated circuit discovery, sparse-feature circuits, and attribution graphs (Conmy et al., 2023; Marks et al., 2025; Lindsey et al., 2025). A useful next layer is not another named unit. It is a population-level graph vocabulary with explicit null models.

Network neuroscience has such a vocabulary. It distinguishes structural, functional, and effective connectivity (Friston, 2011), uses graph-theoretic summaries of brain organization (Bullmore & Sporns, 2009; Bassett & Sporns, 2017), and treats null-model choice as part of the method. The specific primitives include small-world structure, rich clubs, modularity, efficiency, controllability, edge communities, higher-order structure, and time-varying connectivity (Watts & Strogatz, 1998; Humphries & Gurney, 2008; Colizza et al., 2006; van den Heuvel & Sporns, 2013; Newman, 2006; Latora & Marchiori, 2001; Liu et al., 2011; Gu et al., 2015; Faskowitz et al., 2020; Battiston et al., 2020; Lurie et al., 2020). Recent LLM papers already import pieces of this network frame (Liu et al., 2025; Bhandari et al., 2025; Zheng et al., 2025), while adjacent work imports neuroscience-inspired residual-stream dynamics (Fernando & Guitchounts, 2025). Our contribution is the map. It states what has to be specified before these tools become transformer measurements, and which findings would weaken the analogy. The map is a methodological standard and a falsifiable taxonomy rather than a finished empirical result. The analogy holds only once the null-model tests it proposes are passed.

2. Why the Analogy Is Methodological

The relevant parallel is not that transformers are brains. It is that both fields begin with measurable parts, then encounter phenomena where relational structure matters. Neuroscience began with single cells, regions, and lesion effects. Mech-interp began with neurons and attention heads (Olah et al., 2020; Elhage et al., 2021). These primitives were tractable because they could be named, visualised, ablated, and counted.

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Published at the ICML 2026 Workshop on Mechanistic Interpretability, Seoul, South Korea. Copyright 2026 by the author(s).

Table 1. Network-neuroscience primitives become useful transformer measurements only after the graph object, projection, and null model are declared. The import depends on a contract, not a metaphor.

Primitive	Network meaning	Transformer question	Must declare
Connectivity	structural, functional, effective (Friston, 2011)	weights, activation correlations, patching or Jacobian proxies	component set, prompt distribution, proxy/intervention distinction
Small-world	high clustering, short paths (Watts & Strogatz, 1998; Humphries & Gurney, 2008)	distributed routing as width grows	edge-length transform and density-matched null
Rich club	high-degree hubs interconnect (Colizza et al., 2006; van den Heuvel & Sporns, 2013)	redundancy among important heads or features	degree definition and degree-preserving null
Modularity	communities (Newman & Girvan, 2004; Newman, 2006)	functional groups of heads, features, or blocks	directed/weighted modularity null
Participation	connector vs. provincial nodes (Guimerà & Amaral, 2005)	distinguish local specialists from cross-module routers	stable partition and module labels
Efficiency	global/local path efficiency (Latora & Marchiori, 2001)	compare routing reachability across models or tasks	edge-to-distance transform
Controllability	driver nodes and Gramians (Liu et al., 2011; Gu et al., 2015)	candidate steering sets	linearisation regime and behavioural validation
Communication	paths, diffusion, navigation, communicability (Estrada & Hatano, 2008; Seguin et al., 2023)	learned mixtures of routing policies	policy family and held-out target
Motifs	enriched subgraphs (Milo et al., 2002; Sporns & Kötter, 2004)	recurring circuit motifs	motif size with density and layer-order null
Brain disorder connectomics	disorder as connectome disruption (Fornito et al., 2015)	fine-tuning as ΔEC fingerprint	matched base/fine-tuned graphs
Edge-centric FC	edge time series (Faskowitz et al., 2020)	prompt-edge variability and overlapping communities	prompt ensemble and edge feature space
Higher-order/dynamic	simplices and time-varying FC (Battiston et al., 2020; Sizemore et al., 2019; Lurie et al., 2020)	polyadic feature interactions and token-state transitions	filtration and token segmentation

Both fields then met mixed representations. Prefrontal-cortex cells can respond to mixtures of task variables (Rigotti et al., 2013), and transformer neurons can represent more features than there are dimensions through superposition (Elhage et al., 2022). Sparse coding was a natural response in both settings. Overcomplete sparse bases produce V1-like features from natural images (Olshausen & Field, 1996), and sparse autoencoders attempt to recover monosemantic transformer features (Bricken et al., 2023; Templeton et al., 2024). The analogy is useful because the sparse-coding story has known limitations. Non-canonical decompositions, inconsistent feature atlases, underspecified causal roles, and fragile explanations are expected failure modes (Song et al., 2025; Leask et al., 2025; Ma et al., 2025; Sharkey et al., 2025).

Both fields also construct small computational subgraphs. Neuroscience calls enriched recurring subgraphs motifs and compares their z-scores against null ensembles (Milo et al., 2002; Sporns & Kötter, 2004). Mech-interp calls prompt-local subgraphs circuits, estimates them with patching or attribution, and now increasingly automates their discovery (Wang et al., 2023; Conmy et al., 2023; Marks et al., 2025; Ameisen et al., 2025). The overlap is not that every circuit is a motif. It is that circuit work already treats computation as a graph, while network neuroscience supplies population-level statistics and null-model discipline.

The most useful methodological import is therefore not metaphorical. It is a requirement for contracts. A graph claim about a transformer should say which components are nodes, how signed or directed effects become edges, what prompt distribution defines the graph, what null is being used, and which behavioural quantity the graph is supposed to predict. Without this contract, claims about small-worldness, rich clubs, modularity, or controllability mainly report preprocessing choices.

3. Transformer Graph Contracts

A transformer does not induce one graph. It induces many possible graphs. We use $G = (V, E)$ for a task-conditioned directed graph over declared components V, such as neurons, attention heads, SAE features, residual directions, blocks, or attribution-graph nodes. Its adjacency $A \in \mathbb{R}^{n \times n}_{\geq 0}$ records nonnegative edge strength with A_{ij} denoting influence from i to j, self-loops removed unless declared, and token/prompt effects aggregated by a stated statistic after a projection such as absolute patching effect, squared local derivative, or thresholded activation association.

Four choices are needed. First, signed quantities must be projected or separated into positive and negative graphs. Second, directed metrics must not be replaced silently by undirected ones. If symmetrisation is used, it must be declared. Third, binary metrics require a threshold or density target, ideally matched across models, plus a convention for disconnected pairs. Fourth, any null should preserve the relevant architecture, density, degree sequence, and layer order. With those choices fixed, standard graph primitives become

transformer questions rather than informal descriptions.

Which properties a null must preserve depends on the research goal, because a null is only informative about structure it does not already build in. To show that topology exceeds what wiring forces, preserve layer order, layer-pair density, and the directed degree sequence, so that residual small-worldness or rich-club structure is not a restatement of the architecture. A test of whether community structure is functional rather than positional also preserves block membership and connection sparsity, so that modularity is not inherited from depth or from where parameters are nonzero. For claims that routing reflects learned computation rather than activation geometry, preserve the marginal activation and token-frequency statistics of the prompt ensemble, for example by permuting edges within matched activation-norm strata. A directed or causal claim requires a direction-preserving null, never a silent symmetrisation, since an undirected null discards the causal asymmetry under test. The general rule preserves every nuisance property that could produce the effect by construction and randomises only the property whose role is being tested.

Three examples show why the contract matters. In the simplest connected undirected case, small-worldness uses $\sigma = (C/C_{\mathrm{rand}})/(L/L_{\mathrm{rand}})$, where C_{rand} and L_{rand} are null-ensemble expectations. Thresholded disconnected graphs need a declared path convention or an efficiency statistic. Rich-club analysis uses $\Phi_{\mathrm{norm}}(k) = \Phi(k)/\Phi_{\mathrm{rand}}(k)$, so a high-degree "core" is only meaningful against a degree-preserving null. Modularity uses $Q = \sum_{ij}(A_{ij} - \gamma k_i k_j/2m)\delta(c_i, c_j)/(2m)$ in the undirected case (Newman & Girvan, 2004), where $k_i = \sum_j A_{ij}$ is degree, $m = |E|$ is the edge count, c_i is the community label, δ is one for matching labels and zero otherwise, and γ is the resolution parameter, with $\gamma = 1$ recovering standard modularity. Weighted undirected graphs use strengths and total edge weight in the same form, while directed extensions require an explicit directed null.

4. A Worked Effective-Connectivity Proxy

We work through one primitive in detail to make the graph contract of Section 3 concrete. Effective connectivity is the most direct point of contact between the network-neuroscience vocabulary and existing patching-based circuit analysis, and the gradient form exposes the edge-construction choices the contract requires a graph claim to declare, signed versus unsigned effects and proxy versus intervention. The example shows how an edge is built and audited. It does not replace patching, and the two are complementary.

Definition 1 (Gradient effective-connectivity proxy)**.** For upstream components $\mathcal{A}$ and downstream components $\mathcal{B}$ with declared intervention coordinates $a_a(x) \in \mathbb{R}^{d_a}$ and $a_b(x) \in \mathbb{R}^{d_b}$, let $J_{ba}(x)$ be the block Jacobian from $\mathcal{A}$ to $\mathcal{B}$. Define $\mathrm{EC}_{ab}(\mathcal{X}) = \mathbb{E}_{x\sim\mathcal{X}}\|J_{ba}(x)\|_F^2$.

This is a local proxy for effective connectivity, not an intervention. Patching estimates finite causal effects (Goldowsky-Dill et al., 2023; Heimersheim & Nanda, 2024). The Jacobian proxy estimates infinitesimal sensitivity. As a scalar special case, take x as the upstream coordinate vector for a gated-MLP neuron $a_n(x) = \phi(w_{g,n}^\top x)(w_{u,n}^\top x)$. Let $g = w_g^\top x$, $u = w_u^\top x$, and $c = w_g^\top w_u$. Then

$$\left\|\tfrac{\partial a_n}{\partial x}\right\|^2 = \phi'(g)^2 u^2 \|w_g\|^2 + 2\phi'(g)\phi(g)uc + \phi(g)^2\|w_u\|^2. \tag{1}$$

Eq. 1 is an input-sensitivity norm. An edge from upstream direction v_a to this neuron would use the squared directional derivative $|(\phi'(g)uw_g + \phi(g)w_u)^\top v_a|^2$. If measuring transmission into the residual stream, the MLP down-projection must also be included. Pairwise probing scales as $O(P|\mathcal{A}||\mathcal{B}|)$ evaluations. VJP/JVP-based Jacobian extraction can often reduce the number of derivative queries, depending on batching, block size, and memory costs.

5. Testable Translations

Table 2 is the shortest useful output of the map. These are not results. They are testable transformer questions that become meaningful once the graph contract in Section 3 is fixed. Priority reflects how direct the methodological analogy is, not confidence that the claim is true.

Worked protocol. A first instantiation uses attention heads as nodes and held-out patching effects as directed non-negative edges. This is the finite-intervention counterpart to the local Jacobian edge proxy in Section 4. Fix density before computing topology. Use a null that preserves layer order, layer-pair density, and prompt family. The target is held-out patching recovery. The claim fails if the statistic is null-level or adds no prediction beyond component counts.

Reading the catalogue. Priority marks transfer difficulty. Direct rows need only a declared graph, a matched null, and a behavioural target. Moderate rows need stronger validation because communities and routing policies are easier to create through preprocessing. Exploratory rows are stress tests drawn from wiring-cost and time-varying-connectivity debates (Bullmore & Sporns, 2012; Lurie et al., 2020). Negative results remain useful because they mark the boundary of the analogy.

6. Use Case, Related Work, and Limits

A concrete use case is deceptive or refusal fine-tuning. If local MLP interventions fail while attention-path interven-

Table 2. Eight translations turn the analogy into testable transformer questions. Source-backed primitive definitions are in Table 1. This table states proposed transformer tests and failure conditions.

Question	Priority	Claim to test	Would fail if
Small-world scaling	Direct	Effective-connectivity graphs show higher small-world structure than architecture-preserving nulls, and hub summaries improve held-out prediction when per-unit recall degrades.	σ is null-level and hub summaries fail beyond unit baselines.
Rich-club ordering	Direct	High-degree heads, neurons, or features interconnect above degree-preserving nulls and overlap with importance sets above chance.	$\Phi_{\mathrm{norm}}(k) \leq 1$ or overlap is random-level under a held-out importance test.
Modularity	Moderate	Communities align with independently labelled functions such as induction, copying, or refusal routing.	Alignment is random-level under labelled probes.
Communication mixtures	Moderate	Mixtures of shortest-path, diffusion, navigation, and communicability policies predict behaviour better than any single policy.	A single policy matches mixture performance.
Motif enrichment	Moderate	Motif z-score vectors cluster fine-tuned models by behavioural category.	Profiles collapse under calibrated nulls.
Minimum steering set	Moderate	High-controllability nodes overlap with patching-derived steering targets.	Controllability and steering sets are disjoint.
Cost-efficiency	Exploratory	With a declared compute-depth cost, trained models lie closer to the cost-efficiency frontier than matched alternatives.	Reasonable cost definitions remove the effect.
Dynamic topology	Exploratory	Token or prompt segments induce recurring connectivity states with behavioural dwell-time structure.	State labels fail to predict held-out behaviour.

tions recover behaviour, the network-neuroscience vocabulary would describe the result as a change in effective connectivity rather than a single-component effect. If a fine-tune preserves most of the weight geometry while behaviour changes, the functional/effective connectivity distinction of Friston (2011) explains why activation- or intervention-defined routing shifts can be missed by weight-diff audits. If ablating the top predicted components redirects recruitment to nearby alternatives, the phenomenon can be tested as redundancy and, if recruited alternatives form a high-degree core, as rich-club-like redundancy. If refusal is concentrated in a low-rank direction (Arditi et al., 2024), the contrast with distributed routing becomes a topology question rather than a naming dispute.

A minimal report is simple. First, build matched base and fine-tuned graphs under the same component set, prompt distribution, and edge construction. Second, report the effect on local components, graph topology, and behaviour. Third, compare the observed shift with nulls that preserve layer order and density. A fine-tune that changes behaviour while leaving most structural weights similar is then, by analogy, a candidate connectopathy-like connectivity-shift phenotype (Fornito et al., 2015). A model that repairs after head ablation can be tested against redundancy statistics rather than described only as a Hydra effect (Michel et al., 2019; McGrath et al., 2023). The import turns qualitative routing stories into statistics with nulls.

The same frame suggests near-term empirical programs. Measure σ, Φ_{norm}, Q, and E_{glob} on matched effective-connectivity graphs across model scales. Cluster fine-tunes by motif profiles (Milo et al., 2002; Sporns & Kötter, 2004) or edge-centric prompt variability (Faskowitz et al., 2020). Adapt controllability diagnostics and compare them with patching-derived steering targets (Liu et al., 2011; Gu et al., 2015). Use persistent homology on threshold filtrations of EC as a multiscale descriptor of higher-order feature interactions (Sizemore et al., 2019; Battiston et al., 2020). Each starts from a graph already produced by circuit or attribution work and asks a population-level question.

The closest current papers cover one import at a time. Liu et al. (2025) test functional brain-inspired networks, Bhandari et al. (2025) analyse module communities, and Zheng et al. (2025) probes neural topology. Fernando & Guitchounts (2025) use residual-stream dynamics. These papers support the premise, but they do not make graph construction, null choice, and failure criteria the object of the contribution. Existing circuit work already speaks graph language through automated circuit discovery, sparse feature circuits, and attribution graphs (Conmy et al., 2023; Marks et al., 2025; Ameisen et al., 2025; Lindsey et al., 2025). We differ by making the cross-reference itself the contribution. The goal is not to beat these empirical papers, but to give them and their successors a shared vocabulary.

Other adjacent threads clarify the boundary. El et al. (2025) port network science to graph transformers, which is related but targets a different architecture. Connectome-inspired ML runs the reverse direction, using brain wiring to design models (Johnson et al., 2023). SAE critiques and audits identify why a single sparse-feature atlas is not enough (Sharkey et al., 2025; Song et al., 2025; Leask et al., 2025; O'Neill et al., 2025; Ma et al., 2025). Philosophical critiques argue that mechanistic interpretability needs sharper explanatory standards (Williams et al., 2025). Our proposal is one concrete response. Relational explanations should state their graph objects, nulls, and refutation conditions.

The limits are material. The most direct one is that we report no proof-of-concept. The contracts and translations are argued for but not yet demonstrated on a real model, and we treat that demonstration as the immediate next step. A first test is narrow. Start with GPT-2 small, a fixed prompt family, one component space such as attention heads or SAE fea-

tures, and two graph constructions, patching-derived effective connectivity and activation-derived functional connectivity. Report the graph contract, then test small-world scaling and rich-club ordering against density- and architecture-preserving nulls. A positive result shows that a relational descriptor predicts behaviour or scale better than component counts alone. A negative result rules out the simplest topology story before the field builds a more elaborate graph language on top of it. The remaining limits are structural. Transformers are fully observable, discrete, engineered systems, whereas brains are partly observable, continuous, and biologically constrained. A Jacobian proxy is not a causal intervention. Dense attention can make some efficiency statistics trivial. Brain controllability metrics carry known caveats before they port to another nonlinear system (Suweis et al., 2019). These limits define the first checks on the import.

The main methodological risk is the number of degrees of freedom. Graph construction, thresholding, symmetrisation, prompt selection, and null choice can each change the answer. A useful paper should report threshold sensitivity, distinguish between signed and unsigned effects, control for density, and separate discovery from validation. Otherwise, the import risks becoming a vocabulary upgrade without explanatory pressure.

7. Conclusion

The claim is narrow. Network neuroscience does not solve mechanistic interpretability. It gives the field a disciplined relational vocabulary. The useful next step is to choose one primitive in Table 1, define the graph contract, and run the null-model test in Table 2.

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