SCALING NETWORKS THROUGH CATEGORICAL AND GEOMETRIC LENS

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Personal Experiences

My research in the geometric Langlands program has focused on using algebraic formalism to reveal connections between the discrete (number theory) and continuous (topology). In the context of computational theory and neuroscience, I am interested in how **algebraic and categorical models** can explain the **qualitative properties** of modern language models and cognitive networks, and conversely, how **biological realism** is reflected in computational processes.

$$\begin{tikzcd}
 & \text{Categorical} \arrow[dl, bend right] \arrow[dr, bend left] & \\
\text{Congitive} \arrow[rr, leftrightarrow, bend right] & & \text{Computational}
\end{tikzcd}$$

We use *associative memory networks* (Hopfield Networks) as a traceable and interpretable framework for understanding how intrinsic properties can explain the *emergent behaviors* observed in large language models [Kap+20], [SMK23]. This research aims to bridge *cognitive, categorical, and computational* perspectives, particularly in studying *scaling laws* and memory retrieval dynamics. In Section 1, I outline associative memory networks and related theoretical and experimental projects. In Section 2, I discuss how my interdisciplinary background in algebra and geometry positions me uniquely to contribute to this research.

[1]

1. Associative Memory Networks

Associative Memory Networks, or Hopfield Networks, are well-known models where memories are stored and recalled based on Lyapunov energy functions that govern the network's dynamics [Hop84]. The local minima in the energy landscape correspond to stored memories. Recent models, such as Dense Associative Memories, improve memory capacity exponentially to $2^{d/2}$ by modifying the energy dynamics [KH16; Dem+17]. These have been connected to attention mechanisms in transformers [Ram+21], though their full relations remain largely unexplored.

Research Goal: Scaling Properties of Associative Memory and Modern Models. The two key research areas are:

1. *Polytopal Decomposition of Weight Spaces in Toy Models*: We will extend the polytopal weight space decomposition, as present in literature on threshold linear networks, [CLM20], [CGM23], to higher order memory networks, such as *simplicial Hopfield networks* inspired by setwise connection [BF23] or *dense associative memories.* This connects to recent approaches using spline theory to

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understand neural networks, [Bb18], [Bla+22]. We will study how the decomposition changes as the *network size increases.*

2. *Energy Transformer Experiments*: We will evaluate the scaling properties of the *Energy Transformer* [Hoo+23], a model based on dense associative memory principles, hypothesizing across three dimensions: - i) Parameters: increasing parameters increases number of attractors (local minima). - ii) Data: scaling data size will refine attractors, resulting in more meaningful minima. - iii) Compute: increasing compute (depth or iterations) will lead to faster convergence to low-energy retrievals.

We will also investigate how *data augmentation* during training affects memory storage and retrieval efficiency, as in prior work on transformers [AL24]. Finally, the end goal is to provide both empirical and theoretical comparison with modern networks [Hoo+24]; some works which studied scaling properties of memory networks include [ND21], [Niu+24], and [CDB24].

Expected impact: This research will highlight the limitations of synthetic memory networks, especially in their use as proxies for explaining biological networks, see also [KH21]. Finally, it is an interesting problem to create hybrid models that respect biological constraints while maintaining the computational power of synthetic networks.

2. Categorical Models and Homotopy Theory

Categorical approaches have gained momentum as a systematic framework for studying network structures [Gav+24]. This has been particularly successful in the field of *geometric deep learning* [Bro+21], where abstract mathematical structures help describe complex neural networks. We propose to explore *Hopfield networks* using a recent formalism by Manin et al. [MM24], which uses *summing functors* and *Gamma spaces* to model the allocation of resources in neural networks. These concepts will allow us to understand how the complexity of memory networks scales as network size increases. The formalism allows us to study a *homotopy type* - a mathematical construct at a deeper level than *homology*[2]. Homotopy captures invariants of network up to continuous deformations. Previous studies have shown that stimulus space can be reconstructed up to homotopy [Man15].

Research Goal: Homotopical Complexity Under Scaling. This research will investigate how the **homotopical complexity** of memory networks evolves as their size increases. Specifically, we will examine how *memory capacity* correlates with *homotopical invariants* like *Betti numbers* (which measure the number of independent cycles in a space) and *simplicial complexes* (which provide a higher-dimensional generalization of networks). Burns and Fukai have already done early work in this direction [BF23], but much remains to be explored.

Expected Impact. Understanding the scaling properties of homotopy could provide a lens through which to study the behavior of neural networks algebraically.

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