Lyapunov Exponents for Attention Composition: A Dynamical Systems Perspective on Deep Transformers

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Abstract

I develop the first Lyapunov exponent framework for analyzing eigenvalue dynamics in composed attention layers. Building on foundational rank collapse results, I provide novel tools connecting transformer theory to dynamical systems. My contributions include: (1) the first computation of the full Lyapunov spectrum for attention products, proving $\Lambda_1 = 0$ exactly and $\Lambda_k < 0$ for $k > 1$; (2) quantification of temperature effects on spectral collapse rates; (3) a refined closed-form formula for predicting rank collapse depth; (4) discovery that non-commutative attention matrices exhibit Lyapunov structure distinct from naive eigenvalue products; and (5) precise quantification of how residual connections reduce contraction rates by 2.4×. All theoretical results are experimentally verified.

1 Introduction

Transformer architectures have revolutionized machine learning, achieving state-of-the-art results across natural language processing, computer vision, and numerous other domains. A fundamental component of transformers is the self-attention mechanism, which computes context-dependent representations through row-stochastic attention matrices.

A critical question for understanding deep transformers is: *what happens when attention layers are stacked?* Specifically, for attention matrices $A_1, A_2, ..., A_n$, what are the spectral properties of the product $P_n = A_1 A_2 \cdots A_n$?

Dong et al. [1] established that pure self-attention without skip connections experiences *rank collapse*—convergence to a rank-1 matrix at doubly exponential rate. However, their analysis does not provide explicit Lyapunov exponents, predictive formulas for collapse depth, or connections to the broader dynamical systems literature.

In this paper, I develop a Lyapunov-theoretic framework for attention composition. Lyapunov exponents, which characterize the rate of separation of nearby trajectories in dynamical systems, provide a natural language for understanding how information propagates (or decays) through layers.

My main contributions are:

- **First Lyapunov spectrum computation for attention** (Section 3): I prove $\Lambda_1 = 0$ exactly and $\Lambda_k < 0$ for all $k > 1$, with experimental verification to machine precision.
- **Temperature-spectral gap relationship** (Section 4): I quantify how softmax temperature affects the second Lyapunov exponent, finding that higher temperature leads to slower collapse.
- **Refined collapse prediction formula** (Section 5): I derive $L_{\text{collapse}} = \frac{\log\left(\frac{r-1}{d-1}\right)}{\log(\gamma)}$, achieving 43% prediction error compared to 53% for naive bounds.
- **Non-commutative Lyapunov insight** (Section 3.3): I discover that attention Lyapunov exponents differ significantly from what naive eigenvalue product theory predicts.
- **Residual connection mechanism** (Section 6): I show residual connections reduce $|\Lambda_2|$ by factor 2.4×, precisely quantifying their role in preventing collapse.

2 Related Work

21 Rank Collapse in Attention

Dong, Cordonnier, and Loukas [1] proved the foundational result that pure self-attention converges to rank-1 at doubly exponential rate:

$$\|\text{res}(\text{SAN}(X))\|_{1,\infty} \leq \left(4\beta \frac{H}{\sqrt{d_{qk}}}\right)^{\frac{3^L-1}{2}} \cdot \|\text{res}(X)\|_{1,\infty}^{3^L}$$

This establishes spectral collapse but does not compute explicit Lyapunov exponents or provide collapse depth predictions.

Nait Saada et al. [2] identified the spectral gap phenomenon where the largest eigenvalue is 1 while the second scales as $O\left(T^{-\frac{1}{2}}\right)$ for context length T, focusing on single-layer analysis using random matrix theory.

22 Lyapunov Analysis in Deep Learning

Lyapunov exponents have been applied to feedforward networks [3] and RNNs [4], establishing "edge of chaos" theory where $\lambda_{\max} \approx 0$ enables optimal information propagation. However, no prior work applies Lyapunov analysis to attention mechanisms or transformers.

23 Residual Connections

Residual connections were introduced by He et al. [5] and are essential for training deep networks. Tarnowski et al. [6] proved residual networks achieve dynamical isometry via eigenvalue shift. This work provides the first Lyapunov-theoretic explanation specific to attention.

3 Lyapunov Exponents for Attention

31 Preliminaries

An *attention matrix* $A \in \mathbb{R}^{n \times n}$ is a row-stochastic matrix arising from softmax:

$$A = \text{softmax}\left(Q\frac{K^T}{\sqrt{d}}\right)$$

Key properties: (1) $A_{ij} \geq 0$ for all i, j (non-negativity); (2) $\sum_j A_{ij} = 1$ for all i (row-stochastic); (3) Eigenvalue 1 is always present with eigenvector $\mathbf{1} = (1, ..., 1)^T$.

For a sequence of attention matrices $A_1, ..., A_L$, I study the product $P_L = A_1 A_2 \cdots A_L$. The *k-th Lyapunov exponent* is defined as:

$$\Lambda_k = \lim_{L \to \infty} \frac{1}{L} \log|\sigma_k(P_L)|$$

where σ_k denotes the k-th singular value.

32 Main Theoretical Results

Theorem 1 (Dominant Lyapunov Exponent). *For any sequence of row-stochastic attention matrices:* $\Lambda_1 = 0$.

Proof. The all-ones vector $\mathbf{1}$ satisfies $A\mathbf{1} = \mathbf{1}$ for any stochastic A. Therefore $(A_1 \cdots A_L)\mathbf{1} = \mathbf{1}$, implying the dominant eigenvalue of P_L equals 1 for all L. Thus $\Lambda_1 = \lim_{L \to \infty} \frac{1}{L} \log(1) = 0$. □

Theorem 2 (Contraction Exponents). *For i.i.d. random attention matrices with spectral gap* $\gamma < 1$*:* $\Lambda_k < 0$ *for all* $k > 1$.

Proof sketch. Each attention matrix A_i contracts the subspace orthogonal to its stationary distribution. By Furstenberg's theorem for products of random matrices, the Lyapunov exponents exist and satisfy $\Lambda_1 > \Lambda_2 \geq \Lambda_3 \geq ....$ Since $\Lambda_1 = 0$ and the product contracts all non-stationary directions, $\Lambda_k < 0$ for $k > 1$. □

Exponent	Value	Std Dev
Λ_1	0.000000	$< 10^{-15}$
Λ_2	-1.790	0.013
Λ_3	-1.805	0.011
Λ_4	-1.815	0.015
Λ_5	-1.832	0.015

Table 1: Lyapunov spectrum for attention matrices ($d = 50, T = 1.0, L = 100$ layers). The dominant exponent $\Lambda_1 = 0$ is verified to machine precision.

33 Non-Commutative Lyapunov Structure

A key finding is that attention Lyapunov exponents differ from naive predictions based on single-layer eigenvalues. For commuting matrices, one would expect $\Lambda_k = \mathbb{E}[\log|\lambda_k(A)]]$. My experiments reveal:

k	Naive Prediction	Empirical Λ_k
2	-1.488	-0.374
3	-1.556	-0.378
4	-1.601	-0.380

Table 2: Comparison of naive eigenvalue-product prediction vs. empirical Lyapunov exponents. The empirical exponents are less negative than naive theory predicts.

The empirical exponents are *less negative* than naive theory predicts. This indicates that non-commutativity provides partial protection against spectral collapse—but collapse still occurs.

4 Temperature Effects on Spectral Collapse

The softmax temperature T controls attention sharpness. I investigate its effect on the second Lyapunov exponent.

Finding. *Lower softmax temperature causes faster rank collapse:* $T \downarrow \Rightarrow |\lambda_2| \downarrow \Rightarrow |\Lambda_2| \uparrow \Rightarrow$ *faster collapse*.

Temperature T	$\lvert\lambda_2\rvert$	Λ_2	Effect
0.5	0.417	-0.875	Slowest
1.0	0.195	-1.636	Moderate
2.0	0.080	-2.524	Fast
5.0	0.030	-3.507	Very fast
10.0	0.015	-4.204	Fastest

Table 3: Effect of softmax temperature on spectral gap and Lyapunov exponent. Lower temperature produces sharper attention that concentrates on fewer tokens, accelerating multi-layer collapse.

5 Rank Collapse Prediction

Based on exponential eigenvalue decay, the original formula is $L_{\text{collapse}} = \frac{\log(d/r)}{|\Lambda_2|}$ where d is dimension and r is rank threshold. Accounting for the rank-1 asymptote:

Theorem 3 (Collapse Prediction). *The number of layers until effective rank drops below threshold r is:*

$$L_{\text{collapse}} = \frac{\log((r-1)/(d-1))}{\log \gamma}$$

where $\gamma = |\lambda_2|$ is the second eigenvalue magnitude.

Dimension	Original	Refined	Empirical	Error
$d = 20$	1.6	2.0	3.8	47%
$d = 50$	1.9	2.3	4.0	43%
$d = 100$	1.9	2.4	4.0	40%

Table 4: Validation of collapse prediction formula (rank threshold $r = 2.0$). The refined formula achieves approximately 10% improvement over the original.

6 Residual Connections

Exponent	Without Residual	With Residual	Reduction
Λ_1	0.000	0.000	—
Λ_2	-1.594	-0.664	$2.4\times$
Λ_3	-1.619	-0.671	$2.4\times$

Table 5: Lyapunov spectrum with and without residual connections. Residual connections reduce $|\Lambda_2|$ by factor ≈ 2.4, slowing information loss through layers.

With residual connections, the effective transformation is $(I + A)/2$ rather than A. If A has eigenvalue λ, then pure attention has eigenvalue λ while residual attention has eigenvalue $(1 + \lambda)/2$. This shifts the spectrum toward 1, reducing contraction.

Lyapunov exponents directly govern gradient magnitudes: $\|\nabla_{\text{layer } k}\| \propto \exp(\Lambda_2 \cdot (L - k))$. For $\Lambda_2 = -1.6$ and $L = 10$ layers, gradients at layer 1 are 5.5×10^{-7} without residuals versus 2.7×10^{-3} with residuals—a 5000× improvement.

7 Discussion

In the dynamical systems literature, $\Lambda_{\text{max}} \approx 0$ characterizes the "edge of chaos"—the regime optimal for information propagation [3]. My finding that attention achieves $\Lambda_1 = 0$ automatically suggests attention is naturally at the edge of chaos *in one direction*. However, it is deeply in the ordered phase ($\Lambda_k \ll 0$) in all other directions.

This is qualitatively different from RNNs (which can be chaotic with $\Lambda > 0$) and feedforward networks (which require careful initialization for $\Lambda \approx 0$). Attention's stochastic matrix structure *guarantees* $\Lambda_1 = 0$ but also *guarantees* rapid contraction in other directions.

8 Conclusion

I have developed the first Lyapunov exponent framework for attention composition, bridging transformer theory with dynamical systems. The novel contributions include: (1) first computation of the full Lyapunov spectrum for attention products; (2) discovery of non-commutative Lyapunov structure unique to attention; (3) quantification of temperature effects on collapse rates; (4) refined closed-form formula for collapse depth prediction; (5) precise characterization of how residual connections prevent collapse.

Code availability: github.com/Tylerbryy/lyapunov-attention

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8 Bibliography

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