

Provable Failure of Language Models in Learning Majority Boolean Logic via Gradient Descent

Bo Chen^{*} Zhenmei Shi[†] Zhao Song[‡] Jiahao Zhang[§]

Abstract

Recent advancements in Transformer-based architectures have led to impressive breakthroughs in natural language processing tasks, with models such as GPT-4, Claude, and Gemini demonstrating human-level reasoning abilities. However, despite their high performance, concerns remain about the inherent limitations of these models, especially when it comes to learning basic logical functions. While complexity-theoretic analyses indicate that Transformers can represent simple logic functions (e.g., AND, OR, and majority gates) by its nature of belonging to the TC^0 class, these results assume ideal parameter settings and do not account for the constraints imposed by gradient descent-based training methods. In this work, we investigate whether Transformers can truly learn simple **majority** functions when trained using gradient-based methods. We focus on a simplified variant of the Transformer architecture and consider both $n = \text{poly}(d)$ and $n = \exp(\Omega(d))$ number of training samples, where each sample is a d -size binary string paired with the output of a basic majority function. Our analysis demonstrates that even after $\text{poly}(d)$ gradient queries, the generalization error of the Transformer model still remains substantially large, growing exponentially with d . This work highlights fundamental optimization challenges in training Transformers for the simplest logical reasoning tasks and provides new insights into their theoretical limitations.

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