

# Induction Heads as a Primary Mechanism for Pattern Matching in In-context Learning

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## Abstract

Large language models (LLMs) have shown a remarkable ability to learn and perform complex tasks through in-context learning (ICL). However, a comprehensive understanding of its internal mechanisms is still lacking. This paper explores the role of *induction heads* in a few-shot ICL setting. We analyse two state-of-the-art models, Llama-3-8B and InternLM2-20B on abstract pattern recognition and NLP tasks. Our results show that even a minimal ablation of induction heads leads to ICL performance decreases of up to ~32% for abstract pattern recognition tasks, bringing the performance close to random. For NLP tasks, this ablation substantially decreases the model’s ability to benefit from examples, bringing few-shot ICL performance close to that of zero-shot prompts. We further use *attention knockout* to disable specific induction patterns, and present fine-grained evidence for the role that induction mechanism plays in ICL.

## 1 Introduction

Large language models have shown a remarkable ability to learn and perform complex tasks through in-context learning (Brown et al., 2020; Touvron et al., 2023b). In ICL, the model receives a demonstration context and a query question as a prompt for prediction. Unlike supervised learning, ICL utilises the pretrained model’s capabilities to recognise and replicate patterns within the demonstration context, thereby enabling accurate predictions for the query without the use of gradient updates.

Given the success and wide applicability of ICL, much recent research was dedicated to better understanding its properties. Several works explored its connections to gradient descent (Akyürek et al., 2022; Von Oswald et al., 2023; Dai et al., 2022), suggesting that ICL shares fundamental similarities with it, functioning as an implicit form of fine-tuning at inference time. Other works investigated

factors influencing ICL, showing that it is driven by the distributions of the training data (Chan et al., 2022) and scales with model size, revealing new abilities at certain parameter thresholds (Brown et al., 2020; Wei et al., 2022). The properties of demonstration samples during inference also have an effect on ICL performance, with aspects such as label space, input distribution and input-label pairing playing a crucial role (Min et al., 2022; Webson and Pavlick, 2021; Wei et al., 2023b). While this work identified interesting properties of ICL and effective ICL prompting strategies, a comprehensive understanding of its operational mechanisms within the models is still lacking.

Our paper aims to fill this gap, by directly investigating the internal model computations that enable ICL. Our work is inspired by recent research in the field of mechanistic interpretability, which aims to reverse engineer the “algorithm” by which Transformer models process information (Olah et al., 2020; Geva et al., 2023; Wang et al., 2022). As a significant milestone in this area, Elhage et al. (2021) demonstrated the existence of *induction heads* in Transformer LMs. These heads scan the context for previous instances of the current token using a *prefix matching* mechanism, which identifies if and where a token has appeared before. If a matching token is found, the head employs a *copying* mechanism to increase the probability of the subsequent token, facilitating exact or approximate repetition of sequences and embodying the algorithm: [a][b]...[a] → [b]. Building on this foundation, Olsson et al. (2022) hypothesised that induction heads are capable of abstract pattern matching and conducted a qualitative analysis of attention patterns observed in an example from an abstract classification task. They observed that these heads, when focused on the final token, tended to attend to previous instances of the correct label. However, they did not conduct any experiments to verify this. In a related study, Bansal et al. (2022) investigated

which heads were important for NLP tasks and found some degree of overlap between these heads and those that had high scores associated with induction. However, they did not directly assess the contribution of induction heads to ICL performance of the models in these tasks.

To the best of our knowledge, our paper is the first one to directly, empirically link the specific computations performed by induction heads to measurable improvements in ICL performance. We investigate the role of induction heads as an underlying mechanism of few-shot ICL across a range of tasks: (1) abstract pattern recognition tasks; (2) popular NLP tasks. We focus on two state-of-the-art models: Llama-3-8B<sup>1</sup> and InternLM2-20B (Cai et al., 2024). We first compute prefix matching and copying scores for all of their attention heads, and then perform head ablation experiments by removing 1% and 3% of the heads with the highest scores. For the NLP tasks, we additionally conduct experiments with semantically unrelated labels to encourage the models to rely on ICL for task completion. To confirm our hypothesis regarding the specific role of the induction mechanisms in these heads, we further perform *attention knockout* experiments, where we selectively inhibit each token’s ability to attend to any tokens that directly followed tokens similar to the current token. This effectively simulates a loss of function in the prefix matching and copying mechanisms.

We find that the ablation of induction heads results in a substantial decrease in ICL performance, much more so than when an equivalent percentage of random heads are ablated. Additionally, when we block the induction attention pattern in these heads, performance drops to levels comparable to or worse than those seen with full head ablations. The latter confirms not merely the importance of induction heads for ICL, but also the specific role of the prefix matching and copying mechanism, retracing its application at the token level. Our work is thus the first to provide comprehensive experimental evidence, demonstrating (1) the essential role of induction heads in few-shot ICL in large-scale, widely-used LMs and real-world tasks and (2) that induction heads utilise a "fuzzy" version of the prefix matching and copying mechanisms to enable pattern matching. Our code and data are publicly available.<sup>2</sup>

<sup>1</sup><https://ai.meta.com/blog/meta-llama-3/>

<sup>2</sup>Anonymized URL

## 2 Related Work

### 2.1 Factors that influence ICL performance

**Pre-training stage** Chan et al. (2022) showed that ICL is driven by the distributional properties of the training data. They found that the ICL ability emerges when the training data exhibits particular distributional properties, such as items appearing in clusters and having a large number of rarely occurring classes. Brown et al. (2020) demonstrated that the scalability of ICL abilities correlates directly with model size. This observation aligns with Wei et al. (2022), who suggested that LLMs might exhibit "emergent abilities" at certain scales of pretraining or beyond specific parameter thresholds. Lu et al. (2023) proposed that these so-called emergent abilities are often inherent capabilities of the ICL mechanism itself.

**Inference stage** At the inference stage, properties of demonstration samples also influence ICL performance. Min et al. (2022) identified the label space, input distribution, and input-label pairing format as key contributors. Webson and Pavlick (2021) found that models are more sensitive to label choice than the semantics of the instruction templates. Wei et al. (2023b) later revealed that sufficiently large models exhibit an emergent ability to learn input-label mappings, even when the labels are flipped or semantically unrelated. In a follow-up work, fine-tuning models on in-context input-label pairs where the labels are semantically unrelated to the task has been shown to boost performance on unseen ICL tasks (Wei et al., 2023a).

### 2.2 Mechanistic Interpretability

Research in mechanistic interpretability seeks to explain model behaviours in terms of their internal components (Olah et al., 2020). Elhage et al. (2021) were among the first to reverse engineer the computations in Transformer models. They demonstrated that small, attention-only models can be deconstructed into interpretable end-to-end functions, which they refer to as 'circuits'. These circuits represent "paths" through the model, illustrating how attention mechanisms guide the information flow. Through circuit analysis, Elhage et al. not only demonstrated the existence of induction heads but also showed that these heads can operate on different distributions as long as the abstract property of repeated sequences' likelihood holds true. Circuit analysis has since led to the identification of

other behaviours within Transformer models, such as indirect object detection (Wang et al., 2022) and factual association (Meng et al., 2022).

Another recent technique—*attention knockout*—systematically disables specific attention weights to assess their impact on model outputs (Geva et al., 2023). Geva et al. (2023) explored how factual knowledge is extracted from LLMs during inference, by blocking the final position from attending to both subject and non-subject positions across specific layers. Additionally, (Wang et al., 2023) blocked label tokens from accessing prior demonstration text in shallow layers, and demonstrated that label words gather information early in forward propagation.

### 2.3 Induction heads & ICL

Building on Elhage et al.’s work, Olsson et al. (2022) provided initial evidence that induction heads might be an underlying mechanism of ICL, defined as the gradual reduction of loss with increasing token indices. They observed that induction heads emerge early in training, coinciding with significant improvements in the model’s ability to learn from context. They also found that modifying or removing these heads impairs ICL performance, assessed by a heuristic measure of loss reduction. In contrast, we employ a few-shot prompting ICL setting and evaluate ICL performance directly through the model’s accuracy on specific tasks.

Using head importance pruning, Bansal et al. (2022) demonstrated that up to 70% of attention heads and 20% of feed forward layers can be removed from the OPT-66B model (Zhang et al., 2022) with minimal performance decline across various downstream tasks. They uncovered a notable consistency in the relevance of certain attention heads for ICL, irrespective of the task or the number of few-shot examples. They investigated whether these crucial heads were induction heads, finding some degree of overlap with those that had high prefix matching scores. Our research extends these findings by not only identifying induction heads but also conducting ablation studies to directly evaluate their impact on ICL performance in diverse tasks.

In parallel to studies on induction heads, Wang et al. (2023) observed that during ICL, demonstration label words serve as anchors that aggregate and distribute crucial information for the final prediction. Building on this, Yu and Ananiadou

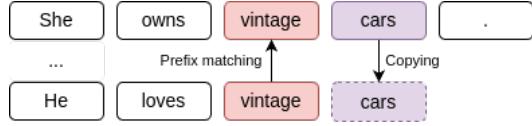


Figure 1: In the sequence "...vintage cars ... vintage," an induction head identifies the initial occurrence of "vintage," attends to the subsequent word "cars" for prefix matching, and predicts "cars" as the next word through the copying mechanism.

(2024) identified specific attention heads, termed "in-context heads", responsible for computing similarity metrics between the input text and each demonstration, subsequently selecting the corresponding labels based on these metrics.

## 3 Background

Elhage et al. (2021) reformulate the operations within a multi-head attention (MHA) layer, which comprises  $H$  attention heads, as follows

$$\sum_{h=1}^H \text{softmax} \left( \frac{\mathbf{x}W_q^h(\mathbf{x}W_k^h)^T}{\sqrt{d_h}} + M^h \right) \mathbf{x}W_v^h W_o^h \quad (1)$$

$$= \sum_{h=1}^H \text{softmax} \left( \frac{\mathbf{x}W_{QK}^h{}^T}{\sqrt{d_h}} + M^h \right) \mathbf{x}W_{OV}^h \quad (2)$$

where  $\mathbf{x} = [\mathbf{x}_1^T, \mathbf{x}_2^T, \dots, \mathbf{x}_N^T]^T \in R^{N \times d}$  represents the sequence of embeddings, with each  $\mathbf{x}_i = \mathbf{t}_i \mathbf{W}_e \in R^{1 \times d}$  denoting the embedding of the  $i$ -th input token  $t_i$ .  $\mathbf{W}_e \in R^{|\mathcal{V}| \times d}$  denotes the embedding matrix over the vocabulary  $\mathcal{V}$ .  $\mathbf{W}_q^h, \mathbf{W}_k^h, \mathbf{W}_v^h \in R^{d \times d_h}$  denote the query, key, and value transformations in the  $h$ -th attention head.  $\mathbf{W}_o \in R^{d \times d}$  represents the output transformation of the MHA layer, and it can be decomposed as  $\mathbf{W}_o = (\mathbf{W}_o^1)^T (\mathbf{W}_o^2)^T \dots (\mathbf{W}_o^H)^T$ , where  $\mathbf{W}_o^h \in R^{d_h \times d}$ .  $M^h$  is a causal attention mask, which ensures each position can only attend to preceding positions (i.e.  $M_{rc}^h = -\infty \forall c > r$  and zero otherwise).

In Equation (1),  $\mathbf{W}_{QK}^h = \mathbf{W}_q^h(\mathbf{W}_k^h)^T$ , termed the Query-Key (QK) circuit, calculates the attention pattern of the  $h$ -th head. The matrix  $\mathbf{W}_{OV}^h = \mathbf{W}_v^h(\mathbf{W}_o^h)^T$ , termed the Output-Value (OV) circuit, determines the independent output for each head for the current token. This output can be projected back to the vocabulary as  $\mathbf{x}W_{OV}^h \mathbf{W}_u$  by the unembedding transformation  $\mathbf{W}_u \in R^{d_x \times |\mathcal{V}|}$ . The projected vector represents the influence of the attention head on the output.

Leveraging this decomposition, Elhage et al. (2021) discovered a distinct behaviour in certain attention heads, which they named *induction heads*. This behaviour emerges when these heads process sequences of the form "[A] [B] ... [A] → ". In these heads, the QK circuit directs attention towards [B], which appears directly after the previous occurrence of the current token [A]. This behaviour is termed "prefix matching". The OV circuit subsequently increases the output logit of the attended token [B], termed "copying". An overview of this mechanism is shown in Figure 1.

## 4 Methods

### 4.1 Models

We utilise two recently developed open-source models, namely Llama-3-8B<sup>3</sup> and InternLM2-20B (Cai et al., 2024), both of which are based on the original Llama (Touvron et al., 2023a) architecture. These models feature grouped-query attention mechanisms (Ainslie et al., 2023) to enhance efficiency. Llama-3-8B, comprises 32 layers, each with 32 attention heads. It has shown superior performance compared to its predecessors, even the larger Llama-2 models.

InternLM2-20B, featuring 48 layers with 48 attention heads each, uses a group size of 8 attention heads. We selected InternLM2-20B for its exemplary performance on the 'Needle-in-the-Haystack' task (Cai et al., 2024), which assesses LLMs' ability to retrieve a single critical piece of information embedded within a lengthy text. This mirrors the functionality of induction heads, which scan the context for prior occurrences of a token to extract relevant subsequent information.

### 4.2 Identifying Induction Heads

To identify induction heads within models, we measure the ability of all attention heads to perform prefix matching on random input sequences.<sup>4</sup> We follow the task-agnostic approach to computing prefix matching scores outlined by Olsson et al. (2022). We argue that focusing solely on prefix matching scores is sufficient for our analysis, as high prefix matching cores specifically indicate induction

<sup>3</sup><https://ai.meta.com/blog/meta-llama-3/>

<sup>4</sup>In this work, the term "induction heads" refers to what we define as behavioural induction heads, not mechanistic ones. A true induction head must be verified mechanistically; however, our analysis employs prefix-matching scores as a proxy. We will continue to use the term "induction heads" for simplicity throughout the rest of the paper.

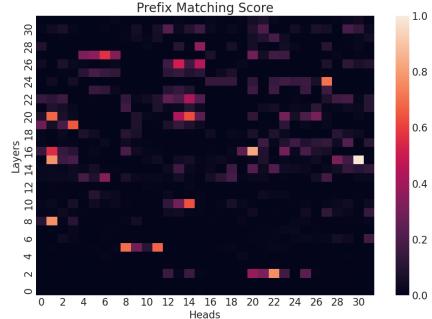


Figure 2: Prefix matching scores for Llama-3-8B.

heads, while less relevant heads tend to show high copying capabilities (Bansal et al., 2022). We generate a sequence of 50 random tokens, excluding the 4% most common and least common tokens. This sequence is repeated four times to form the input to the model. The prefix matching score is calculated by averaging the attention values from each token to the tokens that directly followed the same token in earlier repeats. The final prefix matching scores are averaged over five random sequences.

The prefix matching scores for Llama-3-8B are shown in Figure 2. For InternLM2-20B, we refer to Figure 6 in Appendix A.1. Both models exhibit heads with notably high prefix matching scores, distributed across various layers. In the Llama-3-8B model, ~3% of the heads have a prefix matching score of 0.3 or higher, indicating a degree of specialisation in prefix matching, and some heads have high scores of up to 0.98.

### 4.3 Head Ablations

To investigate the significance of induction heads for a specific ICL task, we conduct zero-ablations of 1% and 3% of the heads with the highest prefix matching scores. This ablation process involves masking the corresponding partition of the output matrix, denoted as  $\mathbf{W}_o^h$  in Eq. 1, by setting it to zero. This effectively renders the heads inactive. As a control condition, we also randomly ablate 1% and 3% of the model's heads, which are selected from any layer except the final layer.

### 4.4 Attention Knockout

To better understand the function of induction heads in few-shot ICL, we conduct *attention knockout* experiments. We hypothesise that when induction heads process a structured dataset, they generate a specific 'induction pattern' by consistently attending back to tokens that previously followed similar ones. Drawing on the methodology of Geva

et al. (2023), we empirically test whether induction heads exhibit this pattern by blocking tokens from attending to tokens that previously followed similar ones. We define two positions  $r, c \in [1, N]$  where  $r < c$ . To inhibit attention, we prevent  $x_c^h$  from attending to  $x_r^h$  in head  $h$  by modifying the attention weights in that layer (Eq. 1) as follows:  $M_{rc}^h = -\infty$ . By comparing the effects of completely removing a head with merely blocking its pattern-directed attention, we can gather empirical evidence suggesting whether these heads predominantly implement this specific induction pattern.

## 5 Ablation Experiments: Abstract Pattern Recognition Tasks

We use a modified version of Eleuther AI’s Language Model Evaluation Harness (Gao et al., 2023) for our experiments. While the default framework randomly samples different in-context examples for each query, we adapted it to ensure a balanced sampling approach, in terms of both the number of examples and classes in the dataset. Aside from this modification, all default settings were maintained.

For predictions, we utilise the harness’s likelihood method, which identifies the target word assigned the largest log probability among all target words. We report accuracy averaged over three random seeds for example selection. For random head ablation, we report accuracy over three ablation seeds, totalling nine runs.

**Datasets** We first conduct ablation experiments on abstract pattern recognition tasks. In these tasks, we expect the model to rely on ICL more so than leveraging information from its training data or weights. The first set of tasks focus on recognising predefined patterns in sequences of letters. In the REPETITION task, the model must determine whether a sequence of four letters consists of repeating two tokens (e.g. A B A B). The RECURSION task involves detecting whether four-letter-sequences contain recursion (e.g. A B B B). In the CENTRE-EMBEDDING task, whether a sequence of five letters contains a centre-embedding (e.g. G L O L G). If the specific pattern is not present in any task, the sequence is a random sequence of letters.

In the second set of tasks, the model is required to label sequences of words that contain a pattern rarely seen in natural language data (i.e. not a common semantic relation). We pair specific semantic categories of words—such as <fruit, animal>, <furniture, profession> (WORDSEQ 1) and <vegetable,

Task	Pattern (Foo)	No pattern (Bar)
Repetition	X H X H	Z E W F
	Q A Q A	F I O E
Recursion	V D D D	N O W T
	F L L L	P Z X F
Centre-embedding	X B V B X	L Q I F P
	V G M G V	H M T B A
Word-sequence classification	grape shark fig panda	couch soldier nightstand writer

Figure 3: Each letter-sequence dataset features examples following the respective patterns labelled ‘Foo’ and random sequences labelled ‘Bar’. For word sequence tasks, examples include pairs of semantically categorised words.

vehicle>, <body part, instrument> (WORDSEQ 2)—and conduct a binary or four-way classification of these pairs. The full datasets for these tasks are shown in Appendix A.3. Figure 3 presents examples from the letter-sequence tasks and one of the word-sequence tasks.

**Experimental Setup** We make use of the semantically unrelated labels “Foo” and “Bar” for all binary tasks. For the 4-way tasks, we additionally use “Mur” and “Res”. For the letter-sequence datasets, we randomly generate sequences of the specified length, ensuring each dataset contains 500 examples with class balance. For the binary word-sequence datasets, we adapted the sampler to ensure it never samples examples with the same instantiation of categories as the query. For instance, “mango monkey: Foo” would not be sampled when the query is “mango shark:”. This adjustment tests whether the induction heads are capable of the fuzzy pattern matching necessary for ICL, rather than just copying. Each binary word-sequence dataset contains 512 examples with class balance and each 4-way word-sequence dataset 1024. Detailed information about the prompts can be found in Appendix A.4.1. We report five- and ten-shot ICL performance for the binary classification tasks, and 20-shot performance for the four-way tasks.

**Llama-3-8B results** The results for Llama-3-8B are presented in Table 1. Few-shot prompting outperforms a zero-shot baseline whose performance is close to random ( $\approx 50\%$ ) across all tasks, showing evidence of ICL. Ablating 1% of induction heads leads to a substantial decrease in performance of up to 31.8% across all tasks and settings. Increasing this to 3% causes a further decline, with the letter-sequence tasks dropping to near-random performance. A similar trend is noted

Llama-3-8B								
Task	Shot	Full model	1% ind. heads	1% ind. pattern	1% rnd. heads	3% ind. heads	3% ind. pattern	3% rnd. heads
Repetition	5	67.3	60.9 (-6.4)	62.5 (-4.8)	68.5 (+1.2)	51.3 (-16.0)	53.2 (-14.1)	68.5 (+1.2)
	10	91.3	59.5 (-31.8)	65.3 (-26.0)	90.3 (-1.0)	54.3 (-37.0)	58.7 (-32.6)	91.2 (-0.1)
Recursion	5	67.8	62.1 (-5.7)	61.5 (-6.3)	69.8 (+2.0)	54.9 (-12.9)	55.1 (-12.7)	70.9 (+3.1)
	10	91.5	66.1 (-25.4)	68.7 (-22.8)	91.5	58.1 (-33.4)	58.9 (-32.6)	92.4 (+0.9)
Centre-embedding	5	58.8	54.0 (-4.8)	55.0 (-3.8)	59.2 (+0.4)	48.3 (-10.5)	50.5 (-8.3)	59.7 (+0.9)
	10	80.4	53.1 (-27.3)	56.5 (-23.9)	81.6 (+1.2)	50.3 (-30.1)	52.3 (-28.1)	80.3 (-0.1)
WordSeq 1 (binary)	5	83.1	72.1 (-11.0)	71.8 (-11.3)	80.6 (-2.5)	54.7 (-28.4)	56.9 (-26.2)	81.0 (-3.1)
	10	99.4	96.4 (-3.0)	97.3 (-2.1)	98.4 (-1.0)	79.2 (-20.2)	82.2 (-17.2)	97.9 (-1.5)
WordSeq 2 (binary)	5	77.9	66.0 (-11.9)	65.2 (-12.7)	74.4 (-3.5)	53.5 (-24.4)	55.7 (-22.2)	75.1 (-2.8)
	10	99.4	95.3 (-4.1)	96.4 (-3.0)	97.3 (-2.1)	77.2 (-22.2)	81.1 (-18.3)	97.6 (-1.8)
WordSeq 1 (4-way)	20	78.3	59.7 (-18.6)	59.8 (-18.5)	71.9 (-6.4)	44.8 (-33.5)	45.2 (-33.1)	72.0 (-6.3)
WordSeq 2 (4-way)	20	81.3	58.6 (-22.7)	59.8 (-21.5)	71.1 (-10.2)	46.5 (-34.8)	47.5 (-33.8)	71.5 (-9.8)
InternLM2-20B								
Task	Shot	Full model	1% ind. heads	1% ind. pattern	1% rnd. heads	3% ind. heads	3% ind. pattern	3% rnd. heads
Repetition	5	68.7	63.3 (-5.4)	62.0 (-6.7)	68.2 (-0.5)	60.8 (-7.9)	58.5 (-10.2)	64.0 (-4.7)
	10	88.1	73.2 (-14.9)	72.1 (-16.0)	87.8 (-0.3)	68.7 (-19.4)	61.2 (-26.9)	84.1 (-4.0)
Recursion	5	68.1	61.4 (-6.7)	59.9 (-8.2)	68.2 (+0.1)	59.6 (-8.5)	55.3 (-12.8)	64.4 (-3.7)
	10	88.5	70.6 (-17.9)	69.9 (-18.6)	87.7 (-0.8)	66.1 (-22.4)	57.1 (-31.4)	84.4 (-4.1)
Centre-embedding	5	59.5	56.3 (-3.2)	56.1 (-3.4)	58.9 (-0.6)	55.1 (-4.4)	54.1 (-5.4)	56.3 (-3.2)
	10	75.3	60.3 (-15.0)	58.5 (-16.8)	74.9 (-0.4)	56.9 (-18.4)	54.3 (-21.0)	71.2 (-4.1)
WordSeq 1 (binary)	5	76.8	67.4 (-9.4)	64.9 (-11.9)	76.7 (-0.1)	59.9 (-16.9)	56.8 (-20.0)	76.9 (+0.1)
	10	95.6	91.7 (-3.9)	88.2 (-7.4)	94.8 (-0.8)	85.7 (-9.9)	83.3 (-12.3)	95.6
WordSeq 2 (binary)	5	83.3	74.8 (-8.5)	70.1 (-13.2)	82.5 (-0.8)	68.6 (-14.7)	64.1 (-19.2)	79.9 (-3.4)
	10	99.0	98.9 (-0.1)	96.8 (-2.2)	96.2 (-2.8)	94.1 (-4.9)	86.7 (-12.3)	98.6 (-0.4)
WordSeq 1 (4-way)	20	77.3	68.8 (-8.5)	65.4 (-11.9)	76.0 (-1.3)	37.3 (-40.0)	37.4 (-39.9)	75.5 (-1.8)
WordSeq 2 (4-way)	20	80.4	78.4 (-2.0)	75.5 (-4.9)	79.3 (-1.1)	52.9 (-27.5)	47.5 (-32.9)	77.3 (-3.1)

Table 1: Llama-3-8B (top) and InternLM2-20B (bottom) ablation experiments on the abstract pattern recognition tasks. For both models, zero-shot performance of the full model is  $\approx 50\%$  in all tasks. Columns labelled ‘1% ind. heads’ and ‘3% ind. heads’ show results from fully ablating 1% and 3% of heads with the highest prefix scores, respectively. ‘1% ind. pattern’ and ‘3% ind. pattern’ columns depict outcomes from blocking induction attention patterns in 1% and 3% of these heads (Sec. 7). Columns ‘1% rnd. heads’ and ‘3% rnd. heads’ illustrate the effects of randomly ablating 1% and 3% of all heads in the model. Performance differences due to the ablation, compared to the full model, are indicated in parentheses.

for the binary word-sequence tasks in the five-shot setting. Though the model achieves near-perfect performance in the ten-shot binary word-sequence tasks, induction head ablations still result in performance declines of up to 22.2%. These substantial performance decreases strongly indicate that induction heads play a crucial role in few-shot ICL. In contrast, the random ablations of 1% and 3% have a much milder impact, reducing performance by no more than 10.2%. This further confirms the importance of specifically induction heads in ICL.

**InternLM2-20B results** The results for InternLM2-20B are presented in Table 1 (bottom). Few-shot prompting consistently outperforms

a (close to random) zero-shot baseline across all tasks, providing clear evidence of ICL. The observed patterns are consistent with those seen in Llama-3-8B: Ablating 1% of induction heads leads to a substantial decrease in performance, though these declines are not as pronounced as those seen in the Llama-3-8B model. The trend persists with the ablation of 3% of induction heads, which results in performance decreases of up to 40%. Ablating 3% of randomly selected heads only results in a performance decrease of up to 4.7%. These findings further affirm that induction heads play a crucial role in few-shot ICL, showing that these results generalise across models.

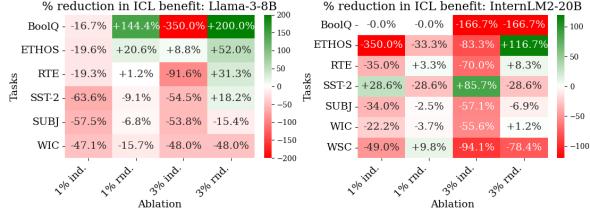


Figure 4: Reduction in ICL benefit for Llama-3-8B and InternLM2-20B, due to head ablations when compared to that of the full model. 1% ind. and 3% ind. denote ablating the top respective percentage of induction heads. 1% rnd. and 3% rnd. denote randomly ablating the respective percentage of all heads in the model.

## 6 Ablation Experiments: NLP Tasks

**Datasets and experimental setup** To assess the impact of induction heads on ICL performance in real-world tasks, we conduct ablation experiments on a range of NLP classification tasks. We make use of the following datasets from the SuperGLUE benchmark (Wang et al., 2019): BoolQ (question answering), RTE (natural language inference), WIC (word-sense disambiguation) and WSC (coreference resolution). Additionally, we include ETHOS (Mollas et al., 2020)<sup>5</sup> (hate speech detection), SST-2 (Socher et al., 2013) (sentiment analysis) and SUBJ (Conneau and Kiela, 2018) (subjectivity). All are binary classification tasks.

For all datasets except SST-2, we map the label space to target words "Yes"/"No", as this has been shown to improve ICL performance (Webson and Pavlick, 2021).<sup>6</sup> For BoolQ, ETHOS and SUBJ, we adopt the "Input/Output" template proposed by Wei et al. (2023b). For the other datasets, we use informative prefixes for each element of the prompt (e.g. 'Premise:'). Our prompts are shown in App. A.4.2. For all tasks, demonstration examples are selected from the training set and evaluations are performed on the validation set. We report ten-shot prompting performance.

We additionally conduct experiments with semantically-unrelated labels (SUL). Specifically, we map the label space from "Yes"/"No" to "Foo"/"Bar". This removes the semantic priors typically provided by labels, forcing the model to rely solely on input-label mappings for ICL (Wei et al., 2023b). Thus, we expect the model to strongly rely on induction heads to recognise patterns.

<sup>5</sup>We employ a 80/20% training-validation split.

<sup>6</sup>For SST-2, we found this to actually lead to poor zero-shot performance, so we use the labels "Positive"/"Negative".

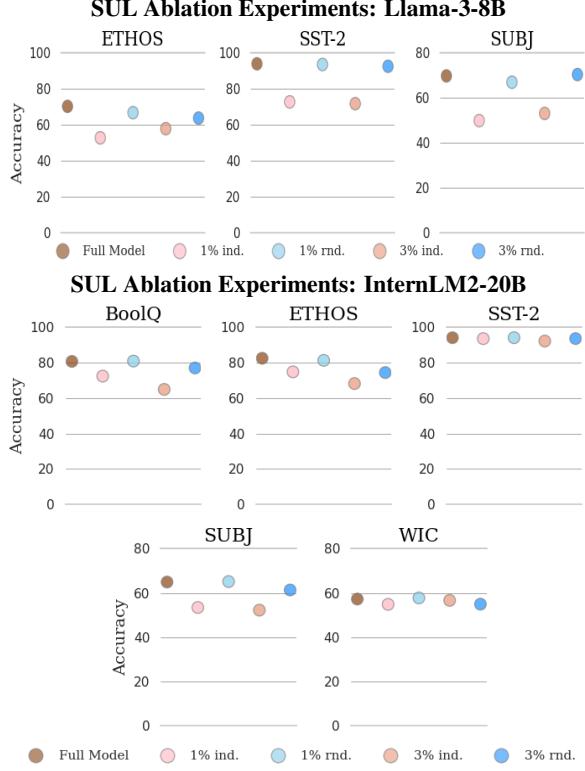


Figure 5: SUL ablation experiments on NLP tasks. 1% ind. and 3% ind. denote ablating the top respective percentage of induction heads. 1% rnd. and 3% rnd. denote randomly ablating the respective percentage of all heads in the model.

**Llama-3-8B Results** We observe ICL benefit (i.e. increase over zero-shot performance) on all tasks except WSC, which we exclude from further analysis. The results for Llama-3-8B on the NLP tasks are presented in Figure 4, which shows percentage decrease in ICL benefit due to ablations. Ablating 1% of induction heads reduces the ICL benefit considerably more than a 1% random ablation across all tasks. For instance, in the SUBJ task, we observe a reduction of 57.5% and only to 6.8% in random head ablation. Increasing the induction head ablation to 3% further decreases the ICL benefit for some tasks. We further verify that for the induction head ablations, the decrease in ICL benefit is due to ten-shot performance being affected more than zero-shot performance for all tasks except ETHOS (App. A.5). Such a pattern is not present in random head ablations. This supports the importance of induction heads for ICL specifically, as opposed to the general functioning of the LLM.

In the SUL setting, the model achieves above-random performance only for the ETHOS, SST-2 and SUBJ tasks, which are presented in Figure 5. Ablating 1% of induction heads leads to substan-

522        tial performance declines of roughly 20% for all  
523        tasks. For random ablations at the same level, these  
524        declines are considerably smaller. These findings  
525        suggest that the model’s capacity to reference pre-  
526        vious examples for learning input-label mappings  
527        may be compromised. Increasing the induction  
528        head ablation to 3% did not reduce performance  
529        further, indicating that the heads responsible are  
530        amongst those with the highest prefix-scores.

531        **InternLM2-20B results** We observe positive ef-  
532        fects of ICL on all tasks with the exceptions of  
533        BoolQ and SST-2, which we therefore exclude  
534        from further analysis. The results in the remaining  
535        tasks are shown in Figure 4. Consistent with obser-  
536        vations from the Llama-3-8B model, we note that:  
537        (1) targeted ablations of induction heads negatively  
538        affect few-shot performance more than zero-shot  
539        performance across all tasks, whereas random ab-  
540        lations do not follow this pattern (App. A.5); (2) a  
541        1% targeted ablation of induction heads diminishes  
542        the ICL benefit considerably more than a 1% ran-  
543        dom ablation. Unlike in Llama-3-8B, increasing  
544        the targeted ablation to 3% further reduces the ICL  
545        benefit in all tasks other than ETHOS.

546        In the SUL setting, the model achieves above-  
547        random performance in all tasks except for WSC  
548        and the results are presented in Fig. 5. A 1% ab-  
549        lation of induction heads results in performance  
550        reductions of up to 18% for all tasks except SST-2.  
551        In most cases, increasing the targeted ablation to  
552        3% leads to additional declines. The random ab-  
553        lations consistently yield much smaller decreases  
554        in performance across all tasks. We observed sim-  
555        ilar trends for the five-shot setting, as shown in  
556        App. A.5. These consistent findings across differ-  
557        ent models and settings reaffirm our conclusions  
558        on the critical role of induction heads in ICL.

## 559        7 Attention Knockout Experiments

560        **Experimental setup** To further explore the func-  
561        tional significance of induction heads, we leverage  
562        the structure of the word-sequence datasets. For  
563        instance, in the binary WORDSEQ 1 task (classifying  
564        <fruit-animal> pairs vs. <furniture-profession>  
565        ones), if an induction head focuses on a *furniture*  
566        token, it should typically attend to *profession* to-  
567        kens that have historically followed *furniture*. To  
568        disrupt this induction pattern, we block attention  
569        from each token to all tokens that directly follow  
570        tokens of the same category, including word cat-  
571        egories, labels, newlines, and colons. In contrast,

572        the letter-sequence tasks require recognising ab-  
573        stract patterns rather than categorical sequences.  
574        Thus, our blocking strategy is exclusively focused  
575        on labels, newlines, and colons.

576        **Llama-3-8B results** Table 1 indicates that when  
577        blocking the induction pattern for 1% of the in-  
578        duction heads, performance declines are within  
579        1.6% of those seen with full head ablations across  
580        all word-sequence task settings. For the letter-  
581        sequence tasks, this margin is slightly larger at  
582        5.8%, which may be attributed to not blocking at-  
583        tention between the letter tokens themselves. Ap-  
584        plying the knockout to 3% of the induction heads  
585        yields performance declines within 4% of full head  
586        ablations across all tasks and settings. The consis-  
587        tent outcomes from both full and pattern-specific  
588        ablations offer strong empirical evidence that induc-  
589        tion heads primarily utilise this attention pattern.

590        **InternLM2-20B results** Table 1 shows that  
591        blocking the induction pattern in 1% of induction  
592        heads results in performance declines within 3.5%  
593        of full head ablations. Unlike in Llama-3-8B, this  
594        approach consistently causes greater performance  
595        decreases than full ablations. This disparity widens  
596        further when the knockout is applied to 3% of the  
597        induction heads. These observations indicate that  
598        for this model, blocking the induction pattern has  
599        a more detrimental impact on head functionality  
600        than eliminating the head entirely, suggesting that  
601        the induction heads are dependent on their specific  
602        operational patterns for performance.

## 603        8 Conclusion

604        In this paper, we explored the extent to which the  
605        prefix matching and copying capabilities of induc-  
606        tion heads play a role in few-shot ICL. Our find-  
607        ings highlight a general trend where even a mini-  
608        mal ablation of just 1% of these heads results in  
609        a substantial decrease in ICL, suggesting that induc-  
610        tion heads are crucial for the model’s few-shot  
611        learning capabilities. Additionally, when the induc-  
612        tion pattern is blocked for a percentage of these  
613        heads, performance drops to levels comparable to  
614        full head ablations. This provides further empi-  
615        rical evidence that induction heads predominantly  
616        utilise this induction pattern and are dependent on  
617        it for optimal performance. Overall, our findings  
618        indicate that induction heads are a fundamental  
619        mechanism underlying ICL.

## 620 Limitations

621 The limitations of this study are twofold. First,  
622 we lack a mechanistic basis for definitively identi-  
623 fying induction heads; instead, we rely on prefix-  
624 matching scores as a proxy. Consequently, it re-  
625 mains unclear how the grouped-query attention  
626 mechanism influences the circuits and whether in-  
627 duction heads form differently as a result. Second,  
628 our investigation of induction attention patterns (at-  
629 tention knockout) is confined to abstract-pattern  
630 recognition tasks. Further research is required to  
631 verify these findings across NLP tasks.

632 Furthermore, it is worth noting that our head ab-  
633 lation and attention knockout experiments demon-  
634 strate that induction heads play an important role in  
635 ICL. However, what we do not test for is whether  
636 they are the only computational process in the  
637 Transformer LM that plays such a role (this can  
638 not in principle be tested by a targeted ablation or  
639 blocking experiment where only a particular part of  
640 the computational process is disabled). Therefore,  
641 it is possible that additional mechanisms and/or cir-  
642 cuits will be discovered in the future that contribute  
643 to ICL, alongside induction heads.

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## A Appendix

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### A.1 Prefix Matching Scores InternLM-20B

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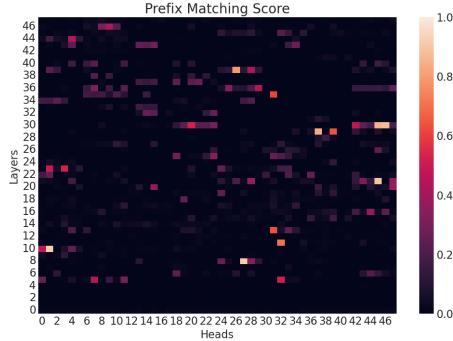


Figure 6: Prefix matching scores for InternLM2-20B

### A.2 Seeds

801

Task	Seeds
Prefix Matching Sequences	0, 1, 2, 3, 4
Demonstration Example Selection	42, 43, 44
Random Head Ablation	42, 43, 44

Table 2: Seed details.

### A.3 Word-sequence datasets

802

#### WordSeq 1 (Binary)

803

```
[ {"text": "cabinet scientist", "label": "Bar" }, {"text": "sofa artist", "label": "Bar" }, {"text": "stool pilot", "label": "Bar" }, {"text": "grape kangaroo", "label": "Foo" }, {"text": "plum tiger", "label": "Foo" }, {"text": "cherry whale", "label": "Foo" }, {"text": "plum giraffe", "label": "Foo" }, {"text": "pear giraffe", "label": "Foo" }, {"text": "kiwi panda", "label": "Foo" }, {"text": "cabinet actor", "label": "Bar" }, {"text": "strawberry elephant", "label": "Foo" }, {"text": "stool carpenter", "label": "Bar" }, {"text": "bed teacher", "label": "Bar" }, {"text": "cherry cat", "label": "Foo" }, {"text": "table engineer", "label": "Bar" }, {"text": "strawberry fox", "label": "Foo" }, {"text": "sofa actor", "label": "Bar" }, {"text": "mango cat", "label": "Foo" }, {"text": "nightstand nurse", "label": "Bar" }, {"text": "cabinet plumber", "label": "Bar" }, {"text": "bench teacher", "label": "Bar" }, {"text": "plum dog", "label": "Foo" }, {"text": "nectarine elephant", "label": "Foo" }, {"text": "apple elephant", "label": "Foo" }, {"text": "dresser nurse", "label": "Bar" }, {"text": "stool artist", "label": "Bar" }, {"text": "grape shark", "label": "Foo" }, {"text": "lemon shark", "label": "Foo" }, {"text": "shelf artist", "label": "Bar" }, {"text": "cabinet pilot", "label": "Bar" }, {"text": "peach monkey", "label": "Foo" }, {"text": "wardrobe engineer", "label": "Bar" }, {"text": "papaya penguin", "label": "Foo" }, {"text": "raspberry dog", "label": "Foo" }, {"text": "nectarine lion", "label": "Foo" }, {"text": "banana tiger", "label": "Foo" }, {"text": "plum cat", "label": "Foo" }, {"text": "sofa doctor", "label": "Bar" }, {"text": "banana horse", "label": "Foo" }, {"text": "shelf actor", "label": "Bar" }, {"text": "pear whale", "label": "Foo" }, {"text": "wardrobe pilot", "label": "Bar" }, {"text": "papaya lion", "label": "Foo" }, {"text": "bench actor", "label": "Bar" }, {"text": "table
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**WordSeq 1 (4-way)**

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}, { "text": "garlic violin", "label": "Mur" }, { "text": "elbow tractor", "label": "Res" 2377
}, { "text": "carrot bus", "label": "Foo" }, {

```

```

2384 "text": "onion accordion", "label": "Mur" }, { "text": "garlic drum", "label": "Mur"
2385 }, { "text": "ankle helicopter", "label": "Res" }, { "text": "tomato boat", "label":
2386 "Foo" }, { "text": "knee accordion", "label": "Bar" }, { "text": "onion motorcycle",
2387 "label": "Foo" }, { "text": "pumpkin accordion", "label": "Mur" }, { "text": "mouth
2388 truck", "label": "Res" }, { "text": "broccoli tractor", "label": "Foo" }, { "text": "
2389 nose piano", "label": "Bar" }, { "text": "mouth train", "label": "Res" }, { "text": "
2390 eggplant flute", "label": "Mur" }, { "text": "pea scooter", "label": "Foo" }, { "
2391 text": "radish clarinet", "label": "Mur" }, { "text": "hand submarine", "label": "
2392 Res" }, { "text": "celery yacht", "label": "Foo" }, { "text": "nose helicopter",
2393 "label": "Res" }, { "text": "pepper violin", "label": "Mur" }, { "text": "onion
2394 saxophone", "label": "Mur" }, { "text": "carrot piano", "label": "Mur" }, { "text": "
2395 beet harp", "label": "Mur" }, { "text": "garlic oboe", "label": "Mur" }, { "text": "
2396 shoulder motorcycle", "label": "Res" }, { "text": "knee train", "label": "Res" },
2397 { "text": "garlic car", "label": "Foo" }, { "text": "knee guitar", "label": "Bar"
2398 }, { "text": "pumpkin clarinet", "label": "Mur" }, { "text": "mouth drum", "label": "
2399 Bar" }, { "text": "radish truck", "label": "Foo" }, { "text": "elbow submarine",
2400 "label": "Res" }, { "text": "eggplant drum", "label": "Mur" }, { "text": "nose
2401 minivan", "label": "Res" }, { "text": "shoulder minivan", "label": "Res" }, { "text": "
2402 broccoli saxophone", "label": "Mur" }, { "text": "potato car", "label": "Foo" },
2403 { "text": "carrot scooter", "label": "Foo" }, { "text": "elbow truck", "label": "Res"
2404 }, { "text": "pumpkin plane", "label": "Foo" }, { "text": "toe saxophone", "label": "
2405 Bar" }, { "text": "cucumber skateboard", "label": "Foo" }, { "text": "neck bicycle",
2406 "label": "Res" }, { "text": "eye trumpet", "label": "Bar" }, { "text": "cucumber
2407 oboe", "label": "Mur" }, { "text": "spinach oboe", "label": "Mur" }, { "text": "
2408 eggplant submarine", "label": "Foo" }, { "text": "ear scooter", "label": "Res" },
2409 { "text": "tomato flute", "label": "Mur" }, { "text": "eggplant guitar", "label": "Mur"
2410 }, { "text": "tomato saxophone", "label": "Mur" }, { "text": "eggplant oboe", "label": "
2411 Mur" }, { "text": "neck trolley", "label": "Res" }, { "text": "broccoli motorcycle",
2412 "label": "Foo" }, { "text": "finger saxophone", "label": "Bar" }, { "text": "ear
2413 minivan", "label": "Res" }, { "text": "lettuce violin", "label": "Mur" }, { "text": "
2414 knee trolley", "label": "Res" }, { "text": "eggplant yacht", "label": "Foo" },
2415 { "text": "foot submarine", "label": "Res" }, { "text": "pepper guitar", "label": "Mur"
2416 }, { "text": "elbow oboe", "label": "Bar" }, { "text": "ankle saxophone", "label": "
2417 Bar" }, { "text": "mouth piano", "label": "Bar" }, { "text": "arm harp", "label": "
2418 Bar" }, { "text": "hand scooter", "label": "Res" }, { "text": "toe drum", "label": "
2419 Bar" }, { "text": "arm minivan", "label": "Res" }, { "text": "lettuce clarinet",
2420 "label": "Mur" }, { "text": "cucumber oboe", "label": "Mur" }, { "text": "potato
2421 motorcycle", "label": "Foo" }, { "text": "shoulder harmonica", "label": "Bar" },
2422 { "text": "broccoli skateboard", "label": "Foo" }, { "text": "neck ukulele", "label": "
2423 Bar" }, { "text": "eye saxophone", "label": "Bar" }, { "text": "pepper trombone",
2424 "label": "Mur" }, { "text": "foot harmonica", "label": "Bar" } ]

```

## A.4 Prompt Examples

We provide five-shot prompting examples for all binary tasks and 20-shot prompting examples for all four-way tasks.

### A.4.1 Abstract Pattern Recognition Tasks

#### Repetition:

Below is a list of various sequences. Your task is to classify each sequence. Use the examples provided to understand how to classify each sequence correctly.

D Y P A: Bar

		2434
M B K O: Bar		2435
P L P L: Foo		2436
V S V S: Foo		2438
S I X P: Bar		2440
J E J E: Bar		2442
<b>Recursion:</b>		2443
Below is a list of various sequences. Your task is to classify each sequence. Use the examples provided to understand how to classify each sequence correctly.		2446
		2447
H U V J: Bar		2448
Q R T K: Bar		2449
X X X X: Foo		2450
U Q Q Q: Foo		2452
O R P L: Bar		2454
V H H H:		2455
<b>Centre-embedding</b>		2456
Below is a list of various sequences. Your task is to classify each sequence. Use the examples provided to understand how to classify each sequence correctly.		2458
		2459
Q T J D G: Bar		2460
R Y P O N: Bar		2461
R Y I Y R: Foo		2462
C B V B C: Foo		2464
W A Y S M: Bar		2466
N F I F N:		2468
<b>Fruit-animal-furniture-profession: Binary Classification</b>		2470
Below is a list of various sequences. Your task is to classify each sequence. Use the examples provided to understand how to classify each sequence correctly.		2472
		2473
strawberry cat: Foo		2475
cherry rabbit: Foo		2476
nightstand nurse: Bar		2477

2486  
2487 grape rabbit: Foo  
2488  
2489 couch artist: Bar  
2490  
2491 cabinet scientist:  
2492  
**2493 Fruit-animal-furniture-profession: Four-way Classification**  
2494 Below is a list of various sequences. Your task is to classify each sequence. Use  
2495 the examples provided to understand how to classify each sequence correctly.  
2496  
2497 papaya writer: Res  
2498  
2499 ottoman zebra: Mur  
2500  
2501 desk chef: Bar  
2502  
2503 mango chef: Res  
2504  
2505 shelf lion: Mur  
2506  
2507 nectarine cat: Foo  
2508  
2509 chair pilot: Bar  
2510  
2511 fig doctor: Res  
2512  
2513 bench scientist: Bar  
2514  
2515 mango horse: Foo  
2516  
2517 chair lawyer: Bar  
2518  
2519 mango lion: Foo  
2520  
2521 chair scientist: Bar  
2522  
2523 couch shark: Mur  
2524  
2525 kiwi farmer: Res  
2526  
2527 cabinet tiger: Mur  
2528  
2529 papaya actor: Res  
2530  
2531 recliner monkey: Mur  
2532  
2533 lemon elephant: Foo  
2534  
2535 desk lawyer: Bar  
2536  
2537 bookcase electrician:

		2538
<b>Vegetable-vehicle-body_part-instrument: Binary Classification</b>		2539
Below is a list of various sequences. Your task is to classify each sequence. Use the examples provided to understand how to classify each sequence correctly.		2540
		2541
potato yacht: Foo		2542
		2543
garlic minivan: Foo		2544
		2545
neck banjo: Bar		2546
		2547
spinach trolley: Foo		2548
		2549
ankle drum: Bar		2550
		2551
arm oboe:		2552
		2553
		2554
<b>Vegetable-vehicle-body_part-instrument: Four-way Classification</b>		2555
Below is a list of various sequences. Your task is to classify each sequence. Use the examples provided to understand how to classify each sequence correctly.		2556
		2557
celery helicopter: Foo		2558
		2559
lettuce violin: Mur		2560
		2561
mouth train: Res		2562
		2563
broccoli bus: Foo		2564
		2565
pumpkin accordion: Mur		2566
		2567
arm accordion: Bar		2568
		2569
foot helicopter: Res		2570
		2571
lettuce trolley: Foo		2572
		2573
eye boat: Res		2574
		2575
mouth piano: Bar		2576
		2577
arm plane: Res		2578
		2579
knee guitar: Bar		2580
		2581
arm plane: Res		2582
		2583
carrot saxophone: Mur		2584
		2585
cucumber scooter: Foo		2586
		2587
eggplant harmonica: Mur		2588
		2589

2590  
2591 garlic scooter: Foo

2592 onion trombone: Mur

2593 toe cello: Bar

2594 arm bicycle: Res

2595 finger submarine:

2596  
2597  
2598  
2599  
2600

#### 2601 A.4.2 NLP Tasks

##### 2602 **BoolQ**

2603 Read the passage and answer the question.

2604  
2605 Input: Natural-born-citizen clause - Status as a natural-born citizen of the  
2606 United States is one of the eligibility requirements established in the United States  
2607 Constitution for holding the office of President or Vice President. This requirement  
2608 was intended to protect the nation from foreign influence.

2609  
2610 Can a canadian be president of the united states?

2611  
2612 Output: No

2613  
2614 Input: Pepsi Zero Sugar - Pepsi Zero Sugar (sold under the names Diet Pepsi  
2615 Max until early 2009 and then Pepsi Max until August 2016), is a zero-calorie,  
2616 sugar-free, carbohydrate-free, ginseng-infused cola sweetened with aspartame,  
2617 marketed by PepsiCo. In Fall 2016, PepsiCo renamed the drink Pepsi Zero Sugar  
2618 from Pepsi Max. It has nearly twice the caffeine of Pepsi's other cola beverages.  
2619 Pepsi Zero Sugar contains 69 milligrams of caffeine per 355ml (12 fl oz), versus 36  
2620 milligrams in Diet Pepsi.

2621  
2622 Is pepsi zero sugar the same as diet pepsi?

2623  
2624 Output: No

2625  
2626 Input: Phone hacking - Phone hacking, being a form of surveillance, is illegal  
2627 in many countries unless it is carried out as lawful interception by a government  
2628 agency. In the News International phone hacking scandal, private investigator Glenn  
2629 Mulcaire was found to have violated the Regulation of Investigatory Powers Act  
2630 2000. He was sentenced to six months in prison in January 2007. Renewed controversy  
2631 over the phone hacking claims led to the closure of the News of the World in July 2011.

2632  
2633 Is it illegal to hack into someones phone?

2634  
2635 Output: Yes

2636  
2637 Input: Legal threat - A legal threat is a statement by a party that it intends  
2638 to take legal action on another party, generally accompanied by a demand that the  
2639 other party take an action demanded by the first party or refrain from taking or  
2640 continuing actions objected to by the demanding party.

Can you threaten to take someone to court?

2641

Output: Yes

2642

Input: Devil's food cake – Devil's food cake is a moist, airy, rich chocolate layer cake. It is considered a counterpart to the white or yellow angel food cake. Because of differing recipes and changing ingredient availability over the course of the 20th century, it is difficult to precisely qualify what distinguishes devil's food from the more standard chocolate cake, though it traditionally has more chocolate than a regular chocolate cake, making it darker. The cake is usually paired with a rich chocolate frosting.

2643

2644

2645

Is devil's food cake the same as chocolate?

2646

Output: No

2647

2648

Input: Ethanol fuel – All biomass goes through at least some of these steps: it needs to be grown, collected, dried, fermented, distilled, and burned. All of these steps require resources and an infrastructure. The total amount of energy input into the process compared to the energy released by burning the resulting ethanol fuel is known as the energy balance (or “energy returned on energy invested”). Figures compiled in a 2007 report by National Geographic Magazine point to modest results for corn ethanol produced in the US: one unit of fossil-fuel energy is required to create 1.3 energy units from the resulting ethanol. The energy balance for sugarcane ethanol produced in Brazil is more favorable, with one unit of fossil-fuel energy required to create 8 from the ethanol. Energy balance estimates are not easily produced, thus numerous such reports have been generated that are contradictory. For instance, a separate survey reports that production of ethanol from sugarcane, which requires a tropical climate to grow productively, returns from 8 to 9 units of energy for each unit expended, as compared to corn, which only returns about 1.34 units of fuel energy for each unit of energy expended. A 2006 University of California Berkeley study, after analyzing six separate studies, concluded that producing ethanol from corn uses much less petroleum than producing gasoline.

2649

2650

2651

2652

2653

Does ethanol take more energy make that produces?

2654

2655

Output:

2656

2657

**ETHOS**  
Does the input contain hate speech?

2658

2659

Input: I see the depression caused her to gain more weight.

2660

2661

Output: No

2662

2663

Input: all mental illnesses are awful and must be treated

2664

2665

Output: Yes

2666

2667

Input: These people are fucking animals they will never change. Our cultures

2668

2669

2670

2693 are simply not compatible. There is definitely a rape culture and it's right  
2694 here with Islam.

2695  
2696 Output: Yes

2698 Input: Even when at the income advantage, niggers still get btfo because  
2699 your race are monkeys trying to do human things. They should be extinguished  
2700

2701 Output: Yes  
2702

2703 Input: I don't see why we don't just create a transgender category. Seems  
2704 the most obvious and fair solution. Great athletes will still compete. And the  
2705 playing field will be as level as can be. I mean we create weight categories  
2706 to maximise the fairness of boxing/mma fights. We recognise that just because two  
2707 people are both male they compete at different levels. We can do the same for  
2708 transgender athletes, surely?

2709  
2710 Output: No  
2711

2712 Input: feminism and Islam are of the same spirit  
2713

2714 Output:  
2715

### 2716 RTE

2717 You are given a premise and a hypothesis. Given the premise, tell me if the  
2718 hypothesis is correct.  
2719

2720 Premise: Les Paul, who continues to perform weekly at New York Iridium Jazz  
2721 Club, has finished recording "Les Paul Friends."  
2722 Hypothesis: Iridium Jazz Club is located in New York.  
2723

2724 Answer: Yes  
2725

2726 Premise: The discovery of the body of a warrior - thought to have died in  
2727 battle more than 2,000 years ago - could help archaeologists to pinpoint the site  
2728 of an ancient holy site. The young warrior, aged about 30, with his spear, a sword,  
2729 his belt and scabbard, stunned archaeologists who found his stone coffin.  
2730 Hypothesis: Altai ice maiden triggers major dispute.  
2731

2732 Answer: No  
2733

2734 Premise: Switzerland has ratified bilateral agreements with the members of  
2735 the European Union in March 2004, but the new members (Cyprus , Czech Republic ,  
2736 Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia and Slovenia) were not  
2737 included in the deal.  
2738 Hypothesis: Lithuania intends to introduce the use of the Euro as an official  
2739 currency on January 1, 2007.  
2740

2741 Answer: No  
2742

2743 Premise: Jill Pilgrim, general counsel of USA Track and Field, brought up  
2744 the issue during a panel on women's sports at the sports lawyers conference. Pilgrim

said the law regarding who is legally considered a woman is changing as sex-change operations become more common.	2745
Hypothesis: Sex-change operations become more common.	2746
Answer: Yes	2747
Premise: Lastly, the author uses the precedent of marijuana legalization in other countries as evidence that legalization does not solve any social problems, but instead creates them.	2748
Hypothesis: Drug legalization has benefits.	2749
Answer: No	2750
Premise: Dana Reeve, the widow of the actor Christopher Reeve, has died of lung cancer at age 44, according to the Christopher Reeve Foundation.	2751
Hypothesis: Christopher Reeve had an accident.	2752
Answer:	2753
<b>SST-2</b>	2754
Classify the review according to its sentiment.	2755
Review: - and especially williams , an american actress who becomes fully english	2756
Sentiment: Positive	2757
Review: each other so intensely , but with restraint	2758
Sentiment: Positive	2759
Review: tear your eyes away	2760
Sentiment: Negative	2761
Review: fascinating and playful	2762
Sentiment: Positive	2763
Review: been discovered , indulged in and rejected as boring before i see this piece of crap again	2764
Sentiment: Negative	2765
Review: it 's a charming and often affecting journey .	2766
Sentiment:	2767
<b>SUBJ</b>	2768
Does the input contain personal opinions, feelings, or beliefs?	2769
Input: by taking entertainment tonight subject matter and giving it humor and	2770

2797 poignancy , auto focus becomes both gut-burstingly funny and crushingly depressing .  
2798  
2799 Output: Yes  
2800  
2801 Input: if you open yourself up to mr . reggio 's theory of this imagery as  
2802 the movie 's set . . . it can impart an almost visceral sense of dislocation and  
2803 change .  
2804  
2805 Output: Yes  
2806  
2807 Input: but for one celebrant this holy week is different .  
2808  
2809 Output: No  
2810  
2811 Input: with grit and determination molly guides the girls on an epic journey  
2812 , one step ahead of the authorities , over 1 , 500 miles of australia 's outback  
2813 in search of the rabbit-proof fence that bisects the continent and will lead them home .  
2814  
2815 Output: No  
2816  
2817 Input: just about all of the film is confusing on one level or another ,  
2818 making ararat far more demanding than it needs to be .  
2819  
2820 Output: Yes  
2821  
2822 Input: pirates of the caribbean is a sweeping action-adventure story set in  
2823 an era when villainous pirates scavenged the caribbean seas .  
2824  
2825 Output:  
2826  
2827 **WIC**  
2828 You are given two sentences and a word. Tell me whether the word has the same meaning  
2829 in both sentences.  
2830  
2831 Word: right  
2832 Sentence 1: He stood on the right.  
2833 Sentence 2: The pharmacy is just on the right past the bookshop.  
2834  
2835 Answer: Yes  
2836  
2837 Word: act  
2838 Sentence 1: She wants to act Lady Macbeth, but she is too young for the role.  
2839 Sentence 2: The dog acts ferocious, but he is really afraid of people.  
2840  
2841 Answer: No  
2842  
2843 Word: fall  
2844 Sentence 1: The hills around here fall towards the ocean.  
2845 Sentence 2: Her weight fell to under a hundred pounds.  
2846  
2847 Answer: No  
2848

Word: Round	2849
Sentence 1: Round off the amount.	2850
Sentence 2: The total is \$25,715 but to keep the figures simple, I'll round it down to \$25,000.	2851
	2852
	2853
Answer: Yes	2854
	2855
Word: have	2856
Sentence 1: What do we have here?	2857
Sentence 2: I have two years left.	2858
	2859
Answer: No	2860
	2861
Word: class	2862
Sentence 1: An emerging professional class.	2863
Sentence 2: Apologizing for losing your temper, even though you were badly provoked, showed real class.	2864
	2865
	2866
Answer:	2867
	2868
<b>WSC</b>	2869
You are given a sentence, a prounoun and a noun. Tell me whether the specified pronoun and the noun phrase refer to the same entity in the sentence.	2870
	2871
	2872
Sentence: Jane knocked on Susan 's door but she did not answer.	2873
Pronoun: she	2874
Noun: Susan	2875
	2876
Answer: Yes	2877
	2878
Sentence: The mothers of Arthur and Celeste have come to the town to fetch them. They are very happy to have them back, but they scold them just the same because they ran away.	2879
	2880
	2881
Pronoun: they	2882
Noun: Arthur and Celeste	2883
	2884
Answer: No	2885
	2886
Sentence: The scientists are studying three species of fish that have recently been found living in the Indian Ocean. They appeared two years ago.	2887
	2888
	2889
Pronoun: They	2890
Noun: The scientists	2891
	2892
Answer: No	2893
	2894
Sentence: Sergeant Holmes asked the girls to describe the intruder . Nancy not only provided the policeman with an excellent description of the heavyset thirty-year-old prowler, but drew a rough sketch of his face.	2895
	2896
	2897
Pronoun: his	2898
Noun: the intruder	2899
	2900
Answer: Yes	

2901

2902 Sentence: The boy continued to whip the pony , and eventually the pony threw  
2903 him over. John laughed out quite loud. "Served him right," he said.

2904 Pronoun: him

2905 Noun: pony

2906

2907 Answer: No

2908

2909 Sentence: Bernard , who had not told the government official that he was  
2910 less than 21 when he filed for a homestead claim, did not consider that he had done  
2911 anything dishonest. Still, anyone who knew that he was 19 years old could take his  
2912 claim away from him .

2913 Pronoun: him

2914 Noun: anyone

2915

2916 Answer:

## A.5 Full NLP ablation experiments

LLama-3-8B						
Task	Shot	Acc	1%	1% rnd.	3%	3% rnd.
BoolQ	0	77.8	76.2 (-1.6)	72.7 (-5.1)	75.2 (-2.6)	71.9 (-5.9)
	5	79.8	77.1 (-2.7)	76.4 (-3.4)	73.0 (-6.8)	77.2 (-2.6)
	10	79.6	77.7 (-1.9)	77.1 (-2.5)	70.7 (-8.9)	77.3 (-2.3)
	SUL	10	46.3	-	-	-
ETHOS	0	70.0	72.0 (+2.0)	68.6 (-1.4)	70.0	62.0 (-8.0)
	5	82.5	82.5	79.5 (-3.0)	81.2 (-1.3)	75.3 (-7.2)
	10	80.2	80.2	80.9 (+0.7)	81.1 (-1.1)	77.5 (-2.7)
	SUL	10	70.3	52.8 (-17.5)	66.8 (-3.5)	57.9 (-12.4)
RTE	0	71.1	67.5 (-3.6)	70.3 (-0.8)	67.9 (-3.2)	67.5 (-3.6)
	5	79.5	75.2 (-4.3)	79.0 (-0.5)	71.6 (-7.9)	78.1 (-1.4)
	10	79.4	74.2 (-5.2)	78.7 (-0.7)	68.6 (-10.8)	78.4 (-1.0)
	SUL	10	52.4	-	-	-
SST-2	0	92.4	92.1 (-0.3)	92.7 (+0.3)	92.2 (-0.2)	91.9 (-0.5)
	5	93.9	92.4 (-1.5)	94.3 (+0.4)	93.0 (-0.9)	93.9
	10	94.6	92.9 (-1.7)	94.7 (+0.1)	93.2 (-1.4)	94.5 (-0.1)
	SUL	10	94.0	72.8 (-21.2)	93.6 (-0.4)	71.8 (-22.2)
SUBJ	0	52.6	53.0 (+0.4)	54.0 (+1.4)	52.4 (-0.2)	53.2 (+0.6)
	5	58.1	53.5 (-4.6)	58.8 (+0.7)	56.3 (-1.8)	56.5 (-1.6)
	10	74.7	62.4 (-12.3)	74.6 (-0.1)	62.6 (-12.1)	71.9 (-2.8)
	SUL	10	69.8	49.9 (-19.9)	67.0 (-2.8)	53.1 (-16.7)
WIC	0	51.4	51.4	51.0 (-0.4)	50.9 (-0.5)	51.7 (+0.3)
	5	59.6	58.2 (-1.4)	59.0 (-0.6)	56.3 (-3.3)	56.8 (-2.8)
	10	61.6	56.8 (-4.8)	59.6 (-2.0)	56.2 (-5.4)	57.0 (-4.6)
	SUL	10	52.6	-	-	-
InternLM2-20B						
Task	Shot	Acc	1%	1% rnd.	3%	3% rnd.
BoolQ	0	88.6	88.6	88.5 (-0.1)	87.7 (-0.9)	86.9 (-1.7)
	5	88.5	88.5	88.6 (+0.1)	88.2 (-0.3)	87.5 (-1.0)
	10	88.3	88.3	88.2 (-0.1)	87.9 (-0.4)	87.1 (-1.3)
	SUL	10	80.7	72.4 (-8.3)	80.9 (+0.2)	64.9 (-15.8)
ETHOS	0	82.0	82.5 (+0.5)	82.5 (+0.5)	82.0	81.5 (-0.5)
	5	84.7	81.3 (-3.4)	84.2 (-0.5)	81.8 (-2.9)	82.6 (-2.1)
	10	82.6	81.0 (-1.6)	82.9 (+0.3)	82.1 (-0.5)	82.8 (+0.2)
	SUL	10	82.5	74.8 (-7.7)	81.3 (-1.2)	68.2 (-14.3)
RTE	0	81.2	80.1 (-1.1)	80.6 (-0.6)	80.5 (-0.7)	79.9 (-1.3)
	5	84.7	82.3 (-2.4)	84.4 (-0.3)	81.4 (-3.3)	84.4 (-0.3)
	10	87.2	84.0 (-3.2)	86.8 (-0.4)	82.3 (-4.9)	86.4 (-0.8)
	SUL	10	80.1	62.9 (-17.2)	81.4 (+1.3)	56.4 (-23.7)
SST-2	0	96.0	96.0	95.7 (-0.3)	95.6 (-0.4)	95.7 (-0.3)
	5	95.1	95.1	95.0 (-0.1)	94.2 (-0.9)	94.9 (-0.2)
	10	95.3	95.1 (-0.2)	95.2 (-0.1)	94.3 (-1.0)	95.2 (-0.1)
	SUL	10	94.1	93.6 (-0.5)	94.1	92.2 (-1.9)
SUBJ	0	61.1	61.7 (+0.6)	61.6 (+0.5)	62.6 (+1.5)	59.9 (-1.2)
	5	75.4	69.6 (-5.8)	75.0 (-0.4)	70.0 (-5.4)	73.4 (-2.0)
	10	81.4	75.1 (-6.3)	81.4	71.3 (-10.1)	78.8 (-2.6)
	SUL	10	64.9	53.4 (-11.5)	65.1 (+0.2)	52.2 (-12.7)
WIC	0	60.8	60.7 (-0.2)	60.8	59.9 (-0.9)	60.1 (-0.7)
	5	68.6	67.2 (-1.4)	68.7 (+0.1)	61.9 (-6.7)	68.9 (+0.3)
	10	68.9	67.0 (-1.9)	68.6 (-0.3)	63.5 (-5.4)	68.3 (-0.6)
	SUL	10	57.2	54.8 (-2.4)	57.7 (+0.5)	56.6 (-0.6)
WSC	0	70.2	67.3 (-2.9)	69.6 (-0.6)	68.3 (-1.9)	70.8 (+0.6)
	5	73.1	68.0 (-5.1)	73.0 (-0.1)	69.6 (-3.5)	73.1
	10	75.3	69.9 (-5.4)	75.2 (-0.1)	68.6 (-1.3)	71.9 (-3.4)
	SUL	10	43.3	-	-	-

Table 3: LLama-3-8B and InternLM2-20B ablation experiments on the NLP tasks. Columns labelled '1% ind. heads' and '3% ind. heads' show the results from fully ablating 1% and 3% of heads with the highest prefix scores, respectively. Columns '1% rnd. heads' and '3% rnd. heads' illustrate the effects of randomly ablating 1% and 3% of all heads in the model. The row 'SUL' denotes settings using semantically unrelated labels. Performance differences due to the ablation, compared to the full model, are indicated in parentheses.

2918      **A.6 Attention Patterns**

2919      **Attention pattern analysis** We conduct a qualitative analysis of the attention patterns exhibited by the  
2920      top five induction heads with the highest prefix matching scores on the 4-way word sequence classification  
2921      dataset. Figure 7 illustrates the attention pattern of the highest scoring induction head for the final token  
2922      of a sample from the dataset. This token predominantly attends to label tokens, particularly focusing on  
2923      "Res," the target label in this instance. Such patterns, while not universally consistent, are particularly  
2924      evident in induction heads located in later layers, suggesting that induction mechanisms may facilitate the  
2925      model's ability to selectively focus on relevant labels in certain contexts.

2926      Furthermore, Figure 8 displays the attention pattern for the 'fig' token. We observe that the head attends  
2927      to tokens that previously followed fruit tokens. This behaviour was consistent across all token categories  
2928      and observed in various heads and samples, suggesting that induction heads not only learn input-label  
2929      mappings, but also grasp the underlying pattern itself. See other attention patterns analysed in this study  
2930      below.

Attention Pattern Layer 15 Head 30 Token 149

```
<|begin_of_text|>
Below
is
a
list
of
various
sequences
Your
task
is
to
classify
each
sequence
Use
the
examples
provided
to
understand
how
to
classify
each
sequence
correctly
shelf
shark
:
Mur
so
fa
cat
:
Mur
c
abinet
shark
:
Mur
pe
ach
lawyer
:
Res
bench
writer
:
Bar
pear
fox
:
Foo
date
kang
aroö
:
Foo
desk
fox
:
Mur
dress
er
writer
:
Bar
str
aw
berry
cat
:
Foo
ottom
an
electric
ian
:
Bar
pl
um
lawyer
:
Res
st
ool
lawyer
:
Bar
apple
chef
:
Res
p
ap
aya
teacher
:
Res
c
ouch
shark
:
Mur
date
elephant
:
Foo
apple
lawyer
:
Res
str
aw
berry
shark
:
Foo
apple
electric
ian
:
Res
fig
soldier
:
```

```
<|begin_of_text|>
Below
is
a
list
of
various
sequences
Your
task
is
to
classify
each
sequence
Use
the
examples
provided
to
understand
how
to
classify
each
sequence
correctly
shelf
shark
:
Mur
so
fa
cat
:
Mur
c
abinet
shark
:
Mur
pe
ach
lawyer
:
Res
bench
writer
:
Bar
pear
fox
:
Foo
date
kang
aroö
:
Foo
desk
fox
:
Mur
dress
er
writer
:
Bar
str
aw
berry
cat
:
Foo
ottom
an
electric
ian
:
Bar
pl
um
lawyer
:
Res
st
ool
lawyer
:
Bar
apple
chef
:
Res
p
ap
aya
teacher
:
Res
c
ouch
shark
:
Mur
date
elephant
:
Foo
apple
lawyer
:
Res
str
aw
berry
shark
:
Foo
apple
electric
ian
:
Res
fig
soldier
:
```

Attention Pattern Layer 15 Head 30 Token 147

```
<|begin_of_text|>
Below
is
a
list
of
various
sequences
Your
task
is
to
classify
each
sequence
Use
the
examples
provided
to
understand
how
to
classify
each
sequence
correctly
shelf
shark
:
Mur
so
fa
cat
:
Mur
c
abinet
shark
:
Mur
pe
ach
lawyer
:
Res
bench
writer
:
Bar
pear
fox
:
Foo
date
kang
aroö
:
Foo
desk
fox
:
Mur
dress
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writer
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Bar
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:
Foo
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an
electric
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Bar
pl
um
lawyer
:
Res
st
ool
lawyer
:
Bar
apple
chef
:
Res
p
ap
aya
teacher
:
Res
c
ouch
shark
:
Mur
date
elephant
:
Foo
apple
lawyer
:
Res
str
aw
berry
shark
:
Foo
apple
electric
ian
:
Res
fig
soldier
:
```

Figure 7: Attention pattern of the final token in head 30 of layer 15 in the Llama-3-8B model.

Figure 8: Attention pattern of the 'fig' token in head 30 of layer 15 in the Llama-3-8B model.

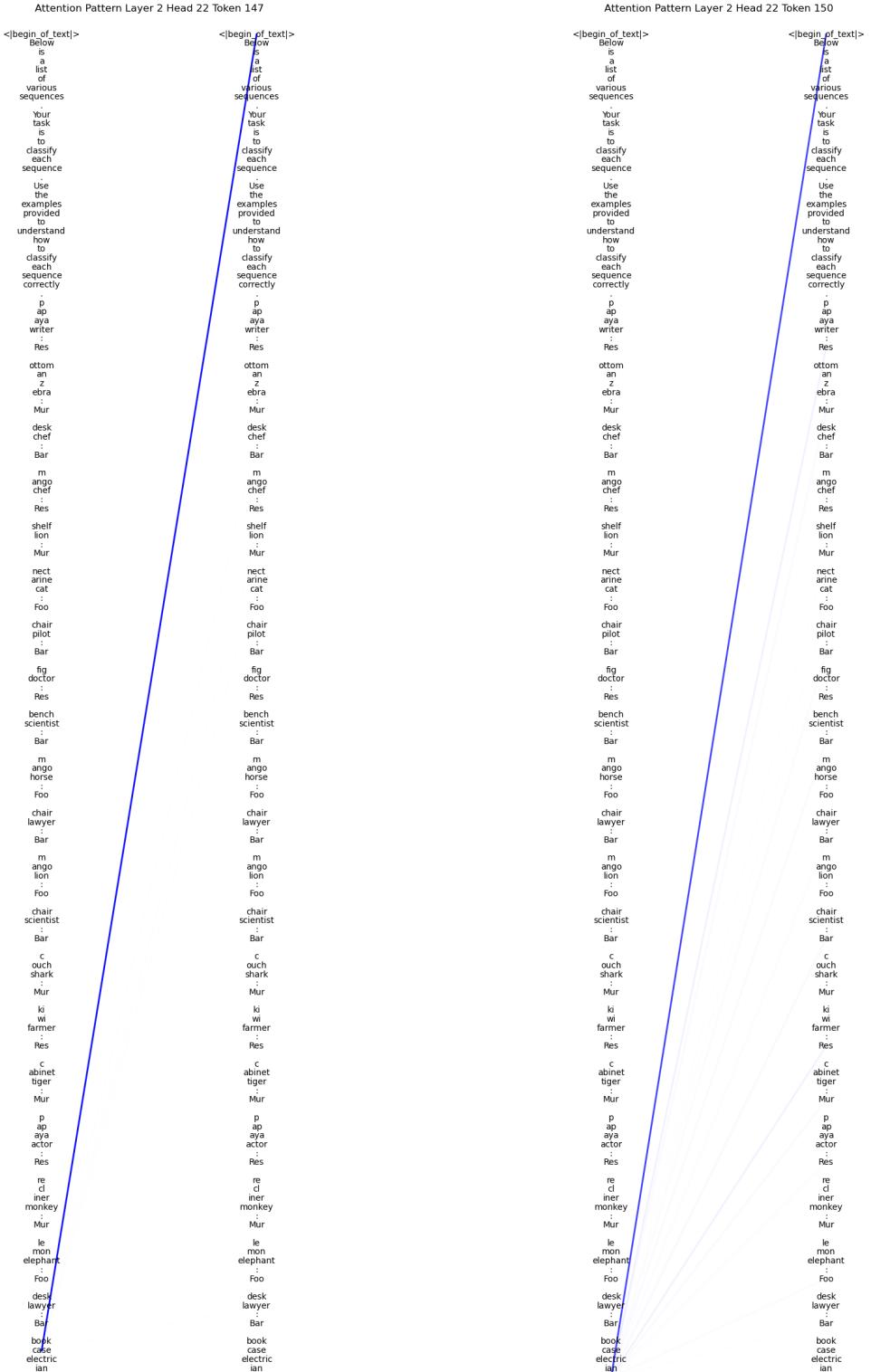


Figure 9: Attention pattern of token 147 in head 22 of layer 2 in Llama-3-8B. Example 1/5.

Figure 10: Attention pattern of token 150 in head 22 of layer 2 in Llama-3-8B. Plot 1/5.

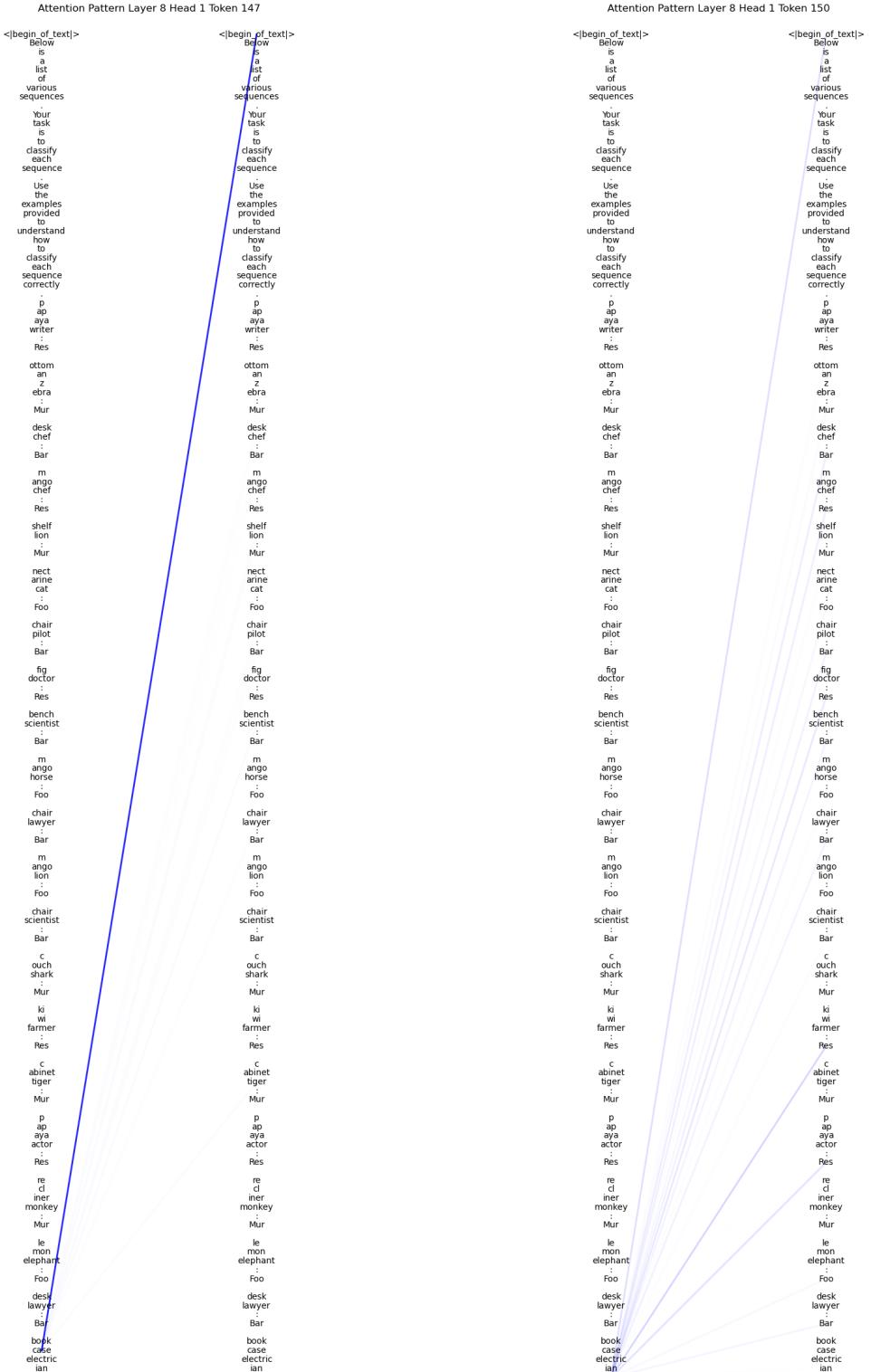


Figure 11: Attention pattern of token 147 in head 1 of layer 8 in Llama-3-8B. Example 1/5.

Figure 12: Attention pattern of token 150 in head 1 of layer 8 in Llama-3-8B. Plot 1/5.

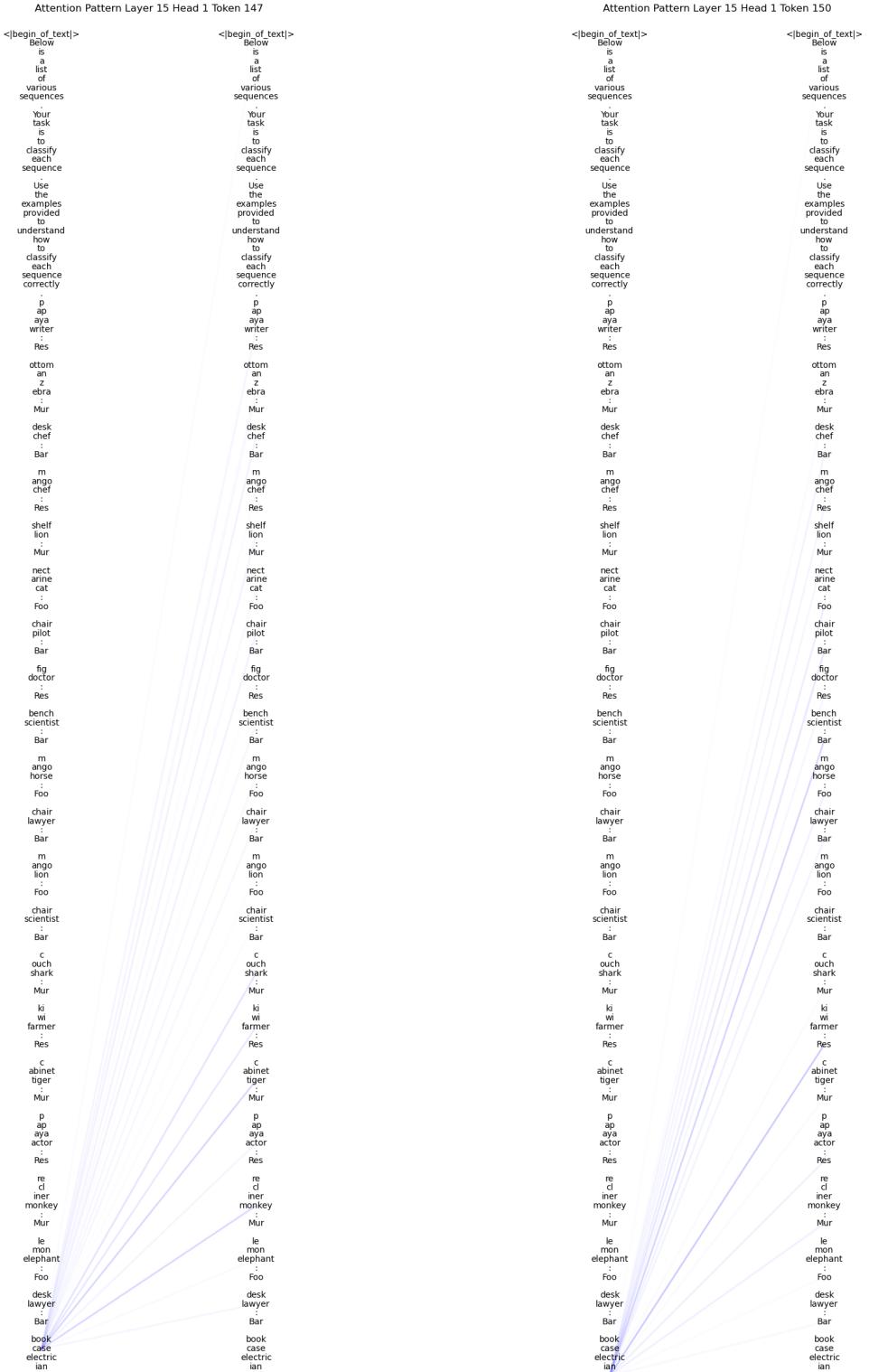


Figure 13: Attention pattern of token 147 in head 1 of layer 15 in Llama-3-8B. Example 1/5.

Figure 14: Attention pattern of token 150 in head 1 of layer 15 in Llama-3-8B. Plot 1/5.

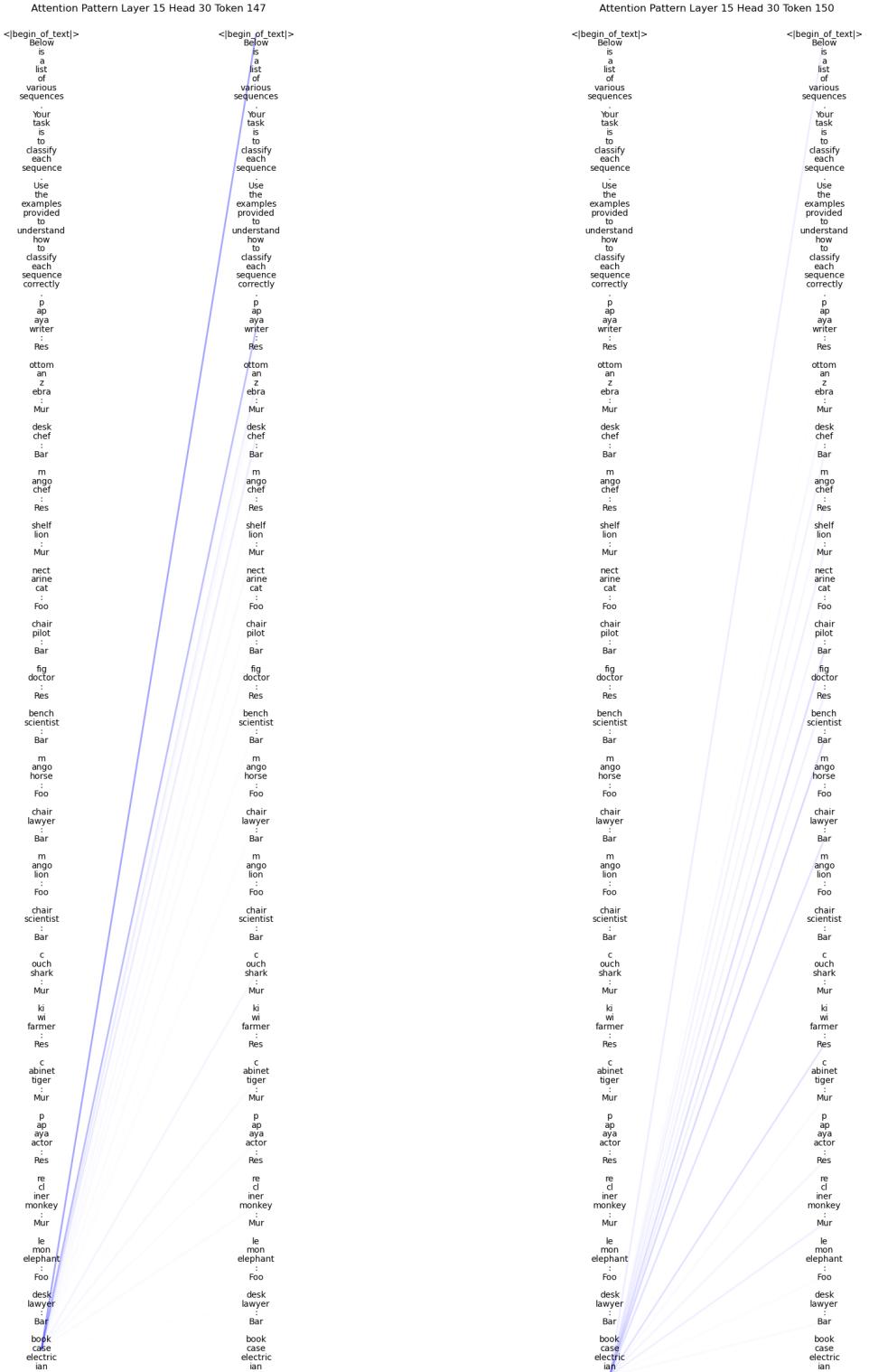


Figure 15: Attention pattern of token 147 in head 30 of layer 15 in Llama-3-8B. Example 1/5.

Figure 16: Attention pattern of token 150 in head 30 of layer 15 in Llama-3-8B. Plot 1/5.

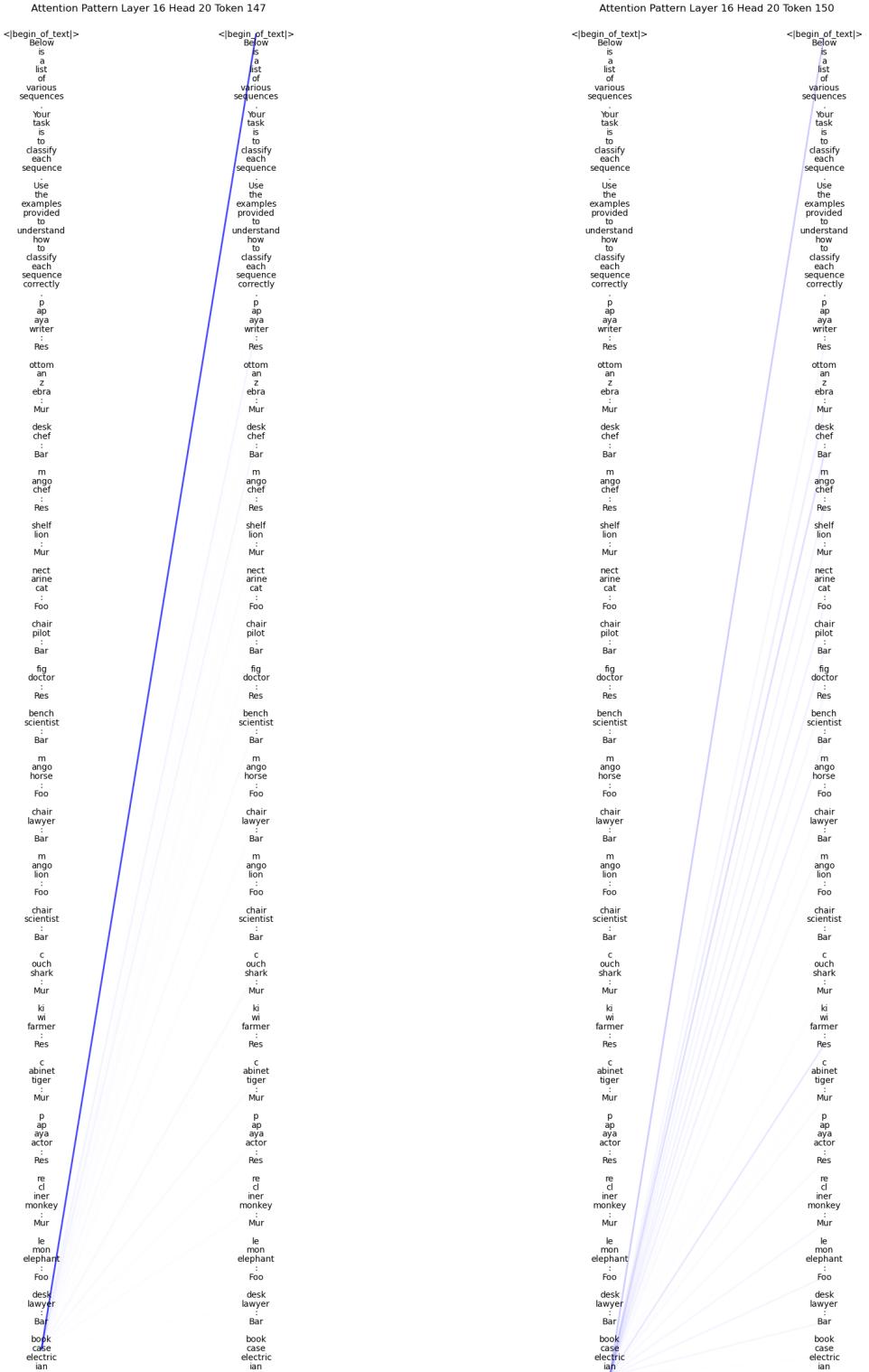


Figure 17: Attention pattern of token 147 in head 20 of layer 16 in Llama-3-8B. Example 1/5.

Figure 18: Attention pattern of token 150 in head 20 of layer 16 in Llama-3-8B. Plot 1/5.

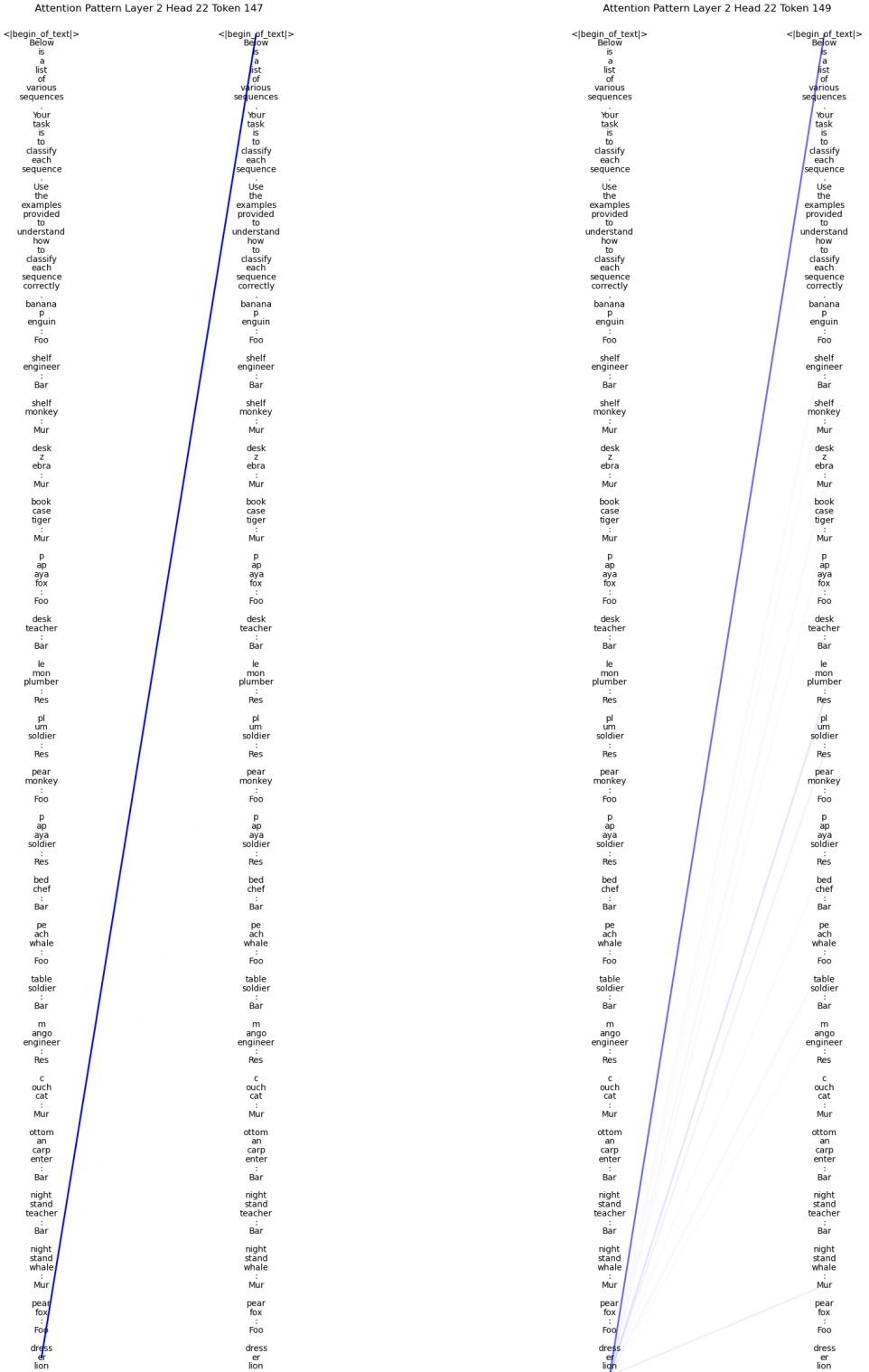


Figure 19: Attention pattern of token 147 in head 22 of layer 2 in Llama-3-8B. Example 2/5.

Figure 20: Attention pattern of token 149 in head 22 of layer 2 in Llama-3-8B. Plot 2/5.

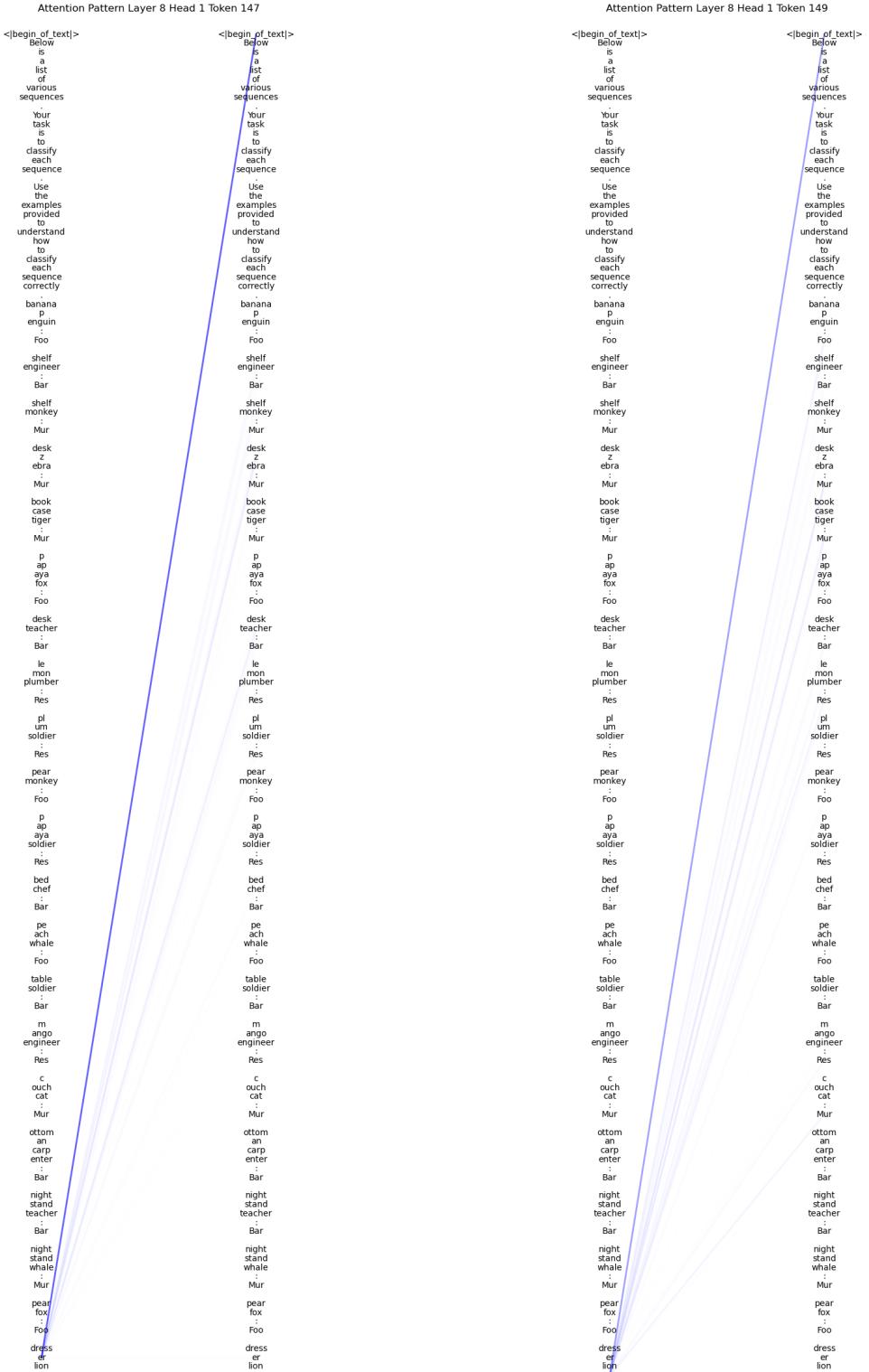


Figure 21: Attention pattern of token 147 in head 1 of layer 8 in Llama-3-8B. Example 2/5.

Figure 22: Attention pattern of token 149 in head 1 of layer 8 in Llama-3-8B. Plot 2/5.

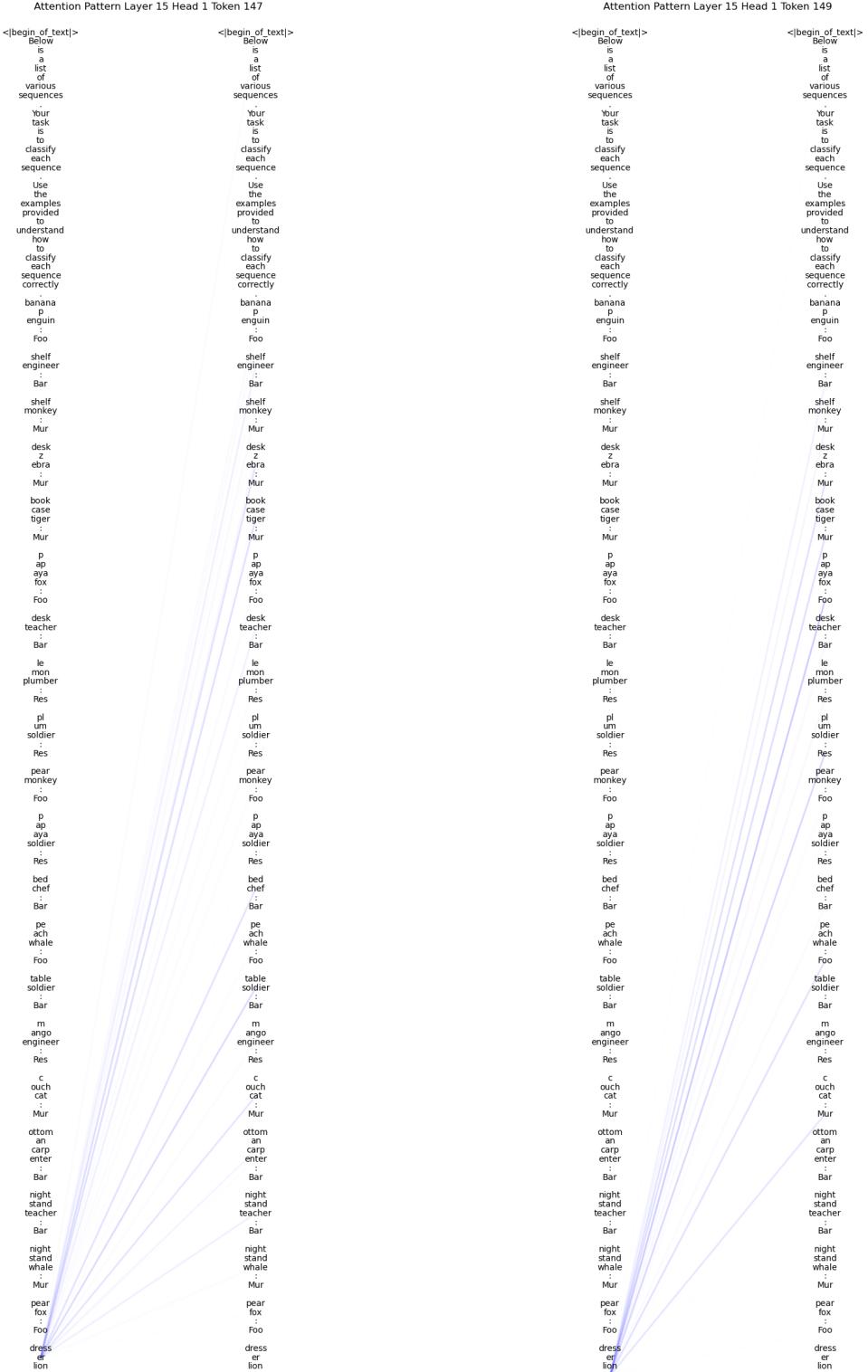


Figure 23: Attention pattern of token 147 in head 1 of layer 15 in Llama-3-8B. Example 2/5.

Figure 24: Attention pattern of token 149 in head 1 of layer 15 in Llama-3-8B. Plot 2/5.

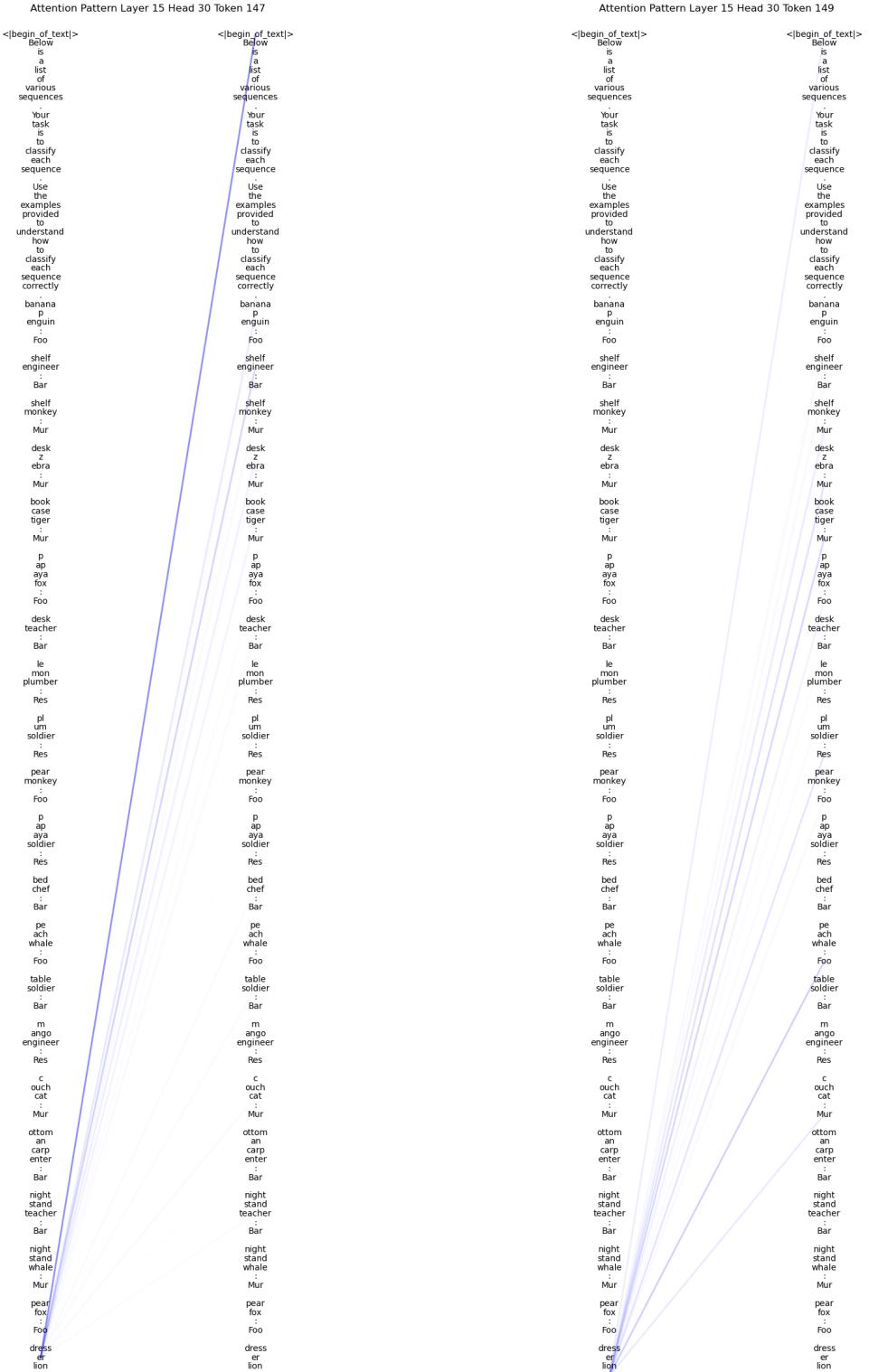


Figure 25: Attention pattern of token 147 in head 30 of layer 15 in Llama-3-8B. Example 2/5.

Figure 26: Attention pattern of token 149 in head 30 of layer 15 in Llama-3-8B. Plot 2/5.

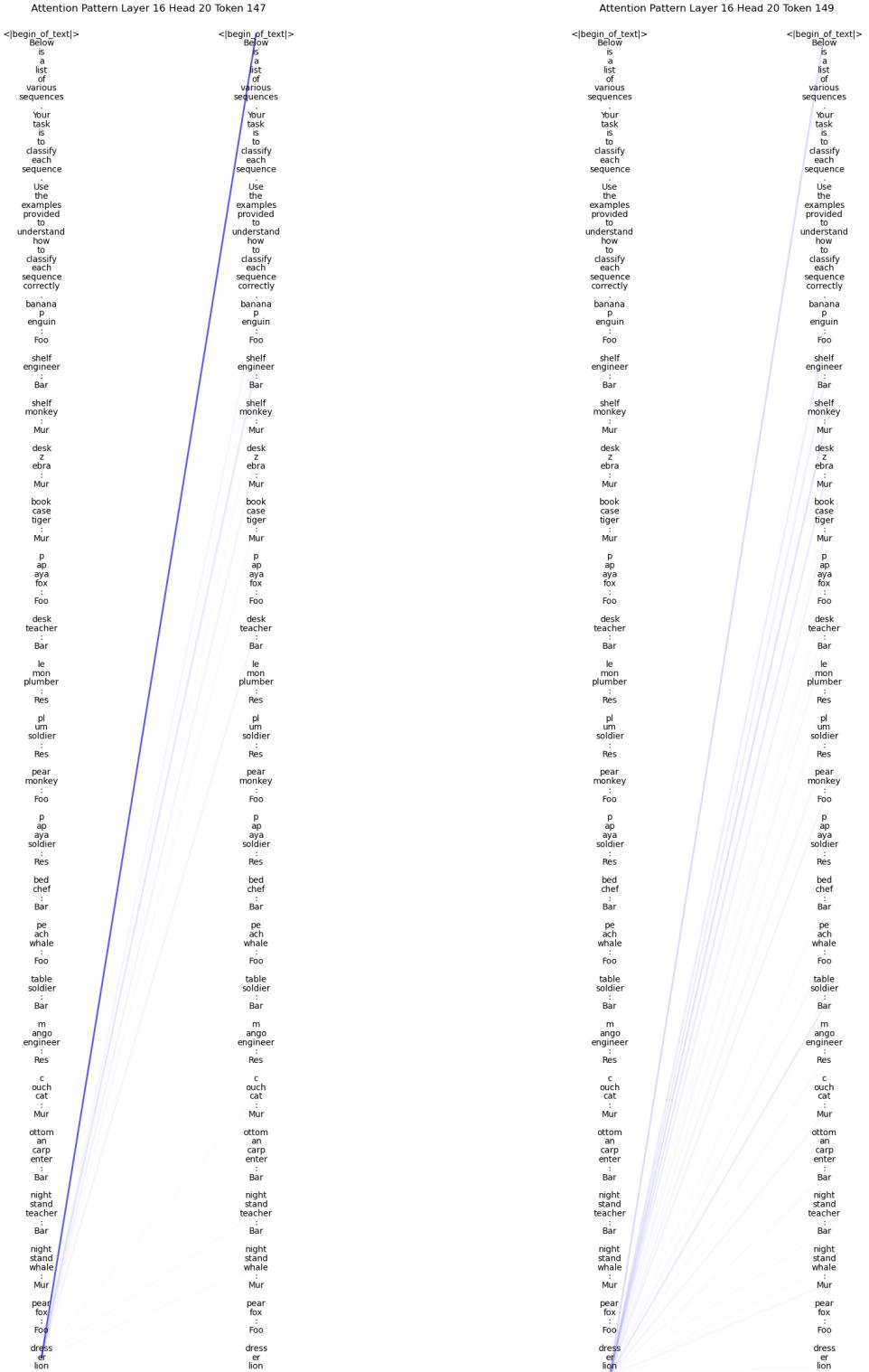


Figure 27: Attention pattern of token 147 in head 20 of layer 16 in Llama-3-8B. Example 2/5.

Figure 28: Attention pattern of token 149 in head 20 of layer 16 in Llama-3-8B. Plot 2/5.

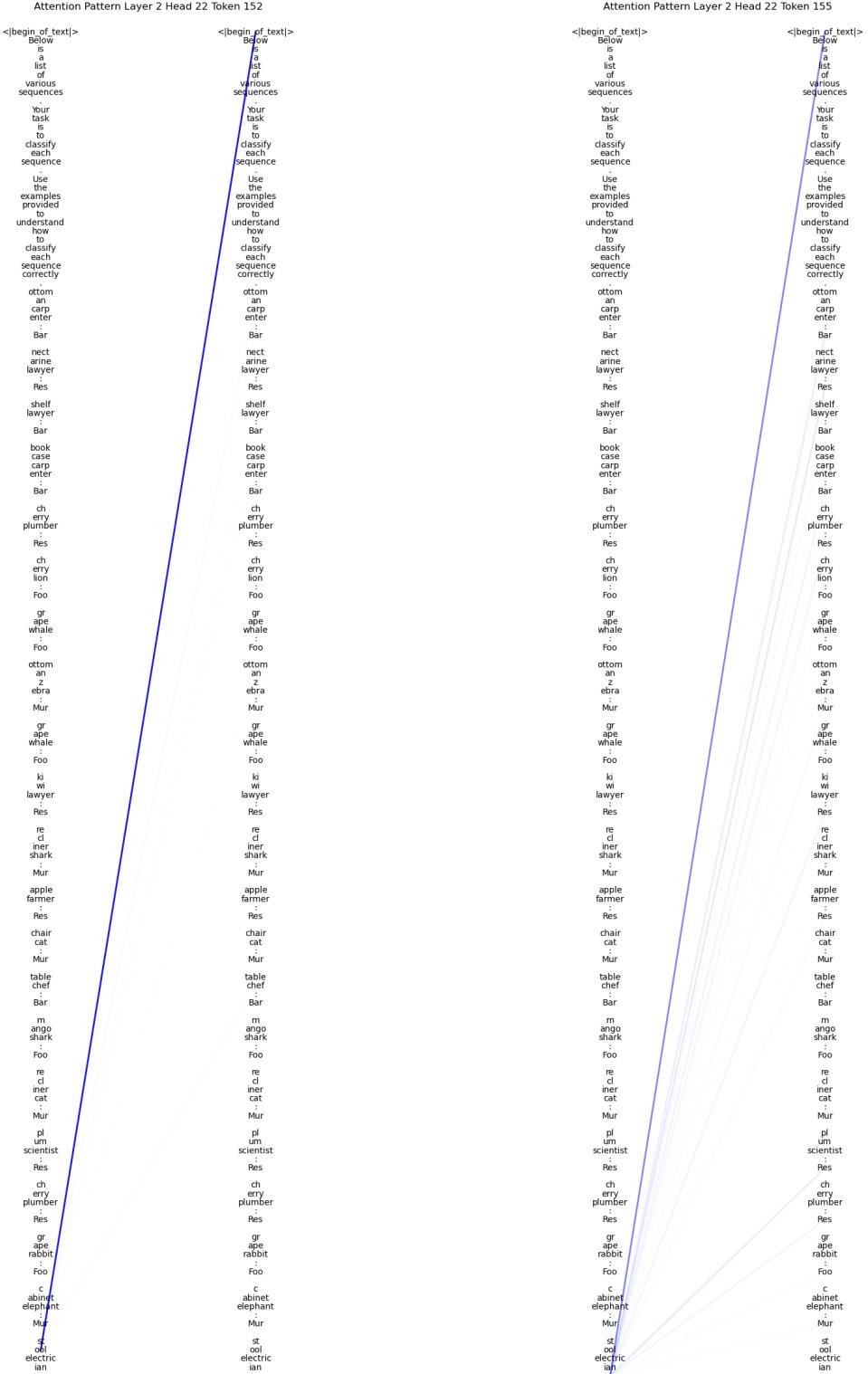


Figure 29: Attention pattern of token 152 in head 22 of layer 2 in Llama-3-8B. Example 3/5.

Figure 30: Attention pattern of token 155 in head 22 of layer 2 in Llama-3-8B. Plot 3/5.

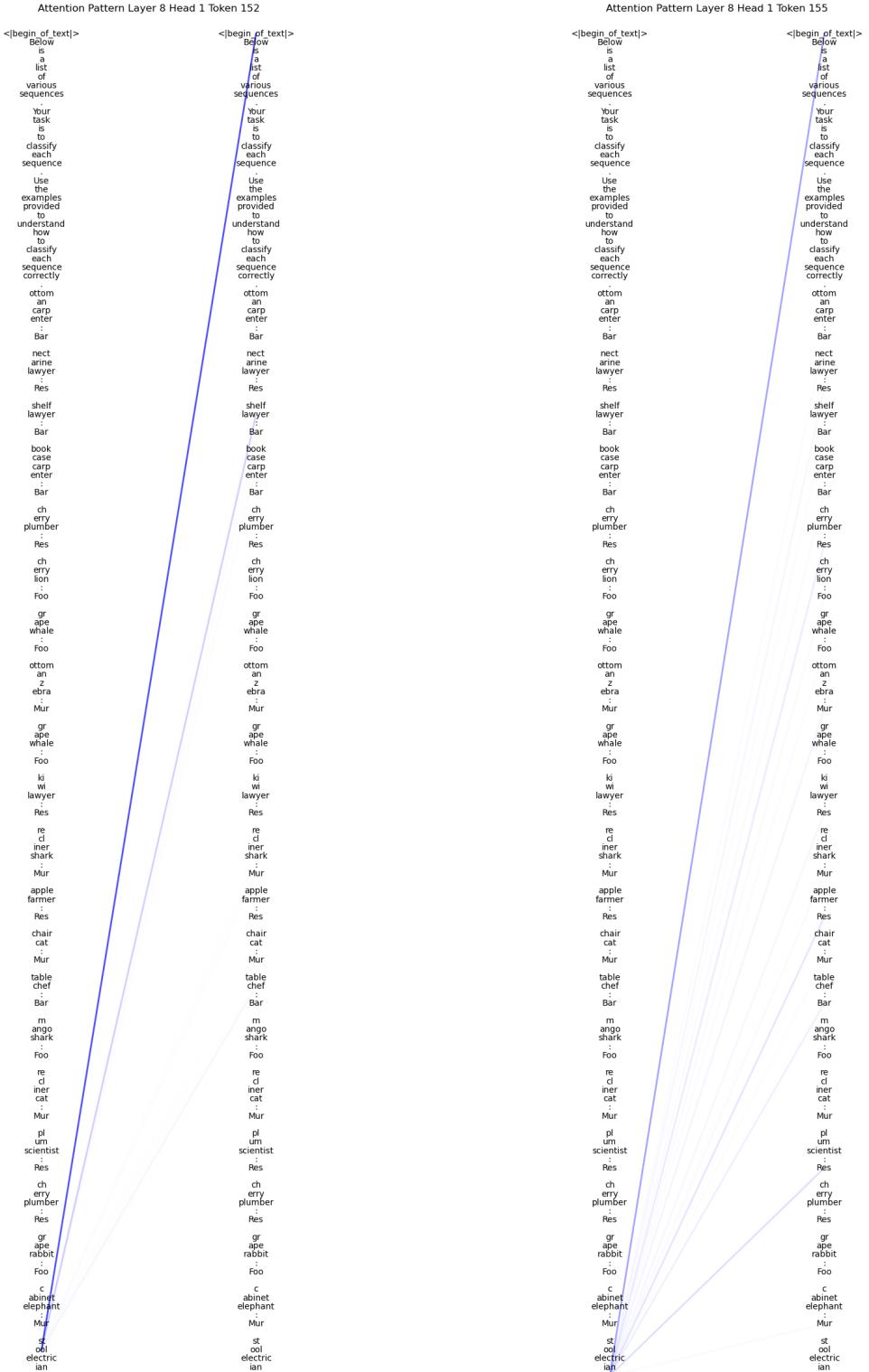


Figure 31: Attention pattern of token 152 in head 1 of layer 8 in Llama-3-8B. Example 3/5.

Figure 32: Attention pattern of token 155 in head 1 of layer 8 in Llama-3-8B. Plot 3/5.

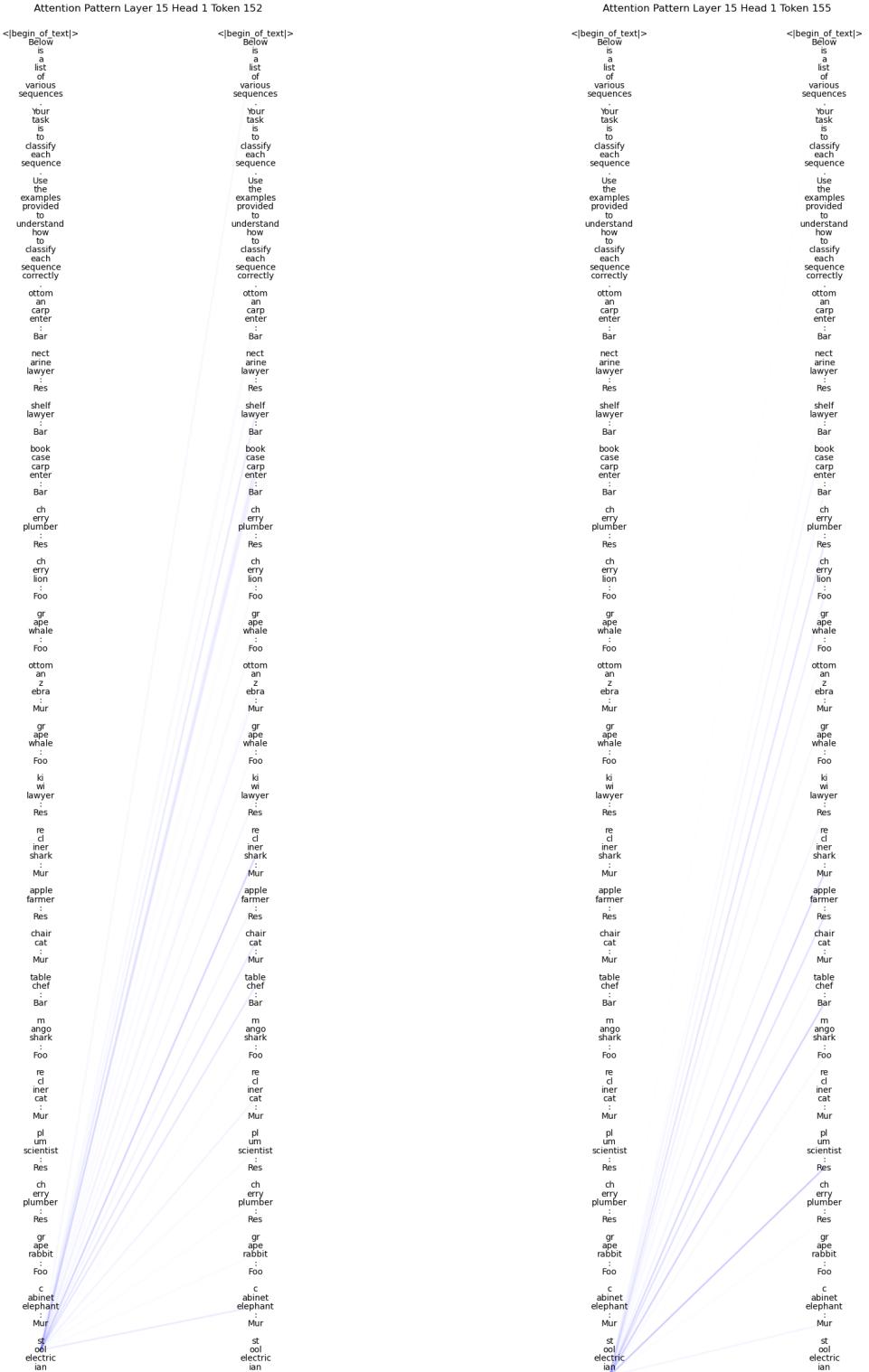


Figure 33: Attention pattern of token 152 in head 1 of layer 15 in Llama-3-8B. Example 3/5.

Figure 34: Attention pattern of token 155 in head 1 of layer 15 in Llama-3-8B. Plot 3/5.

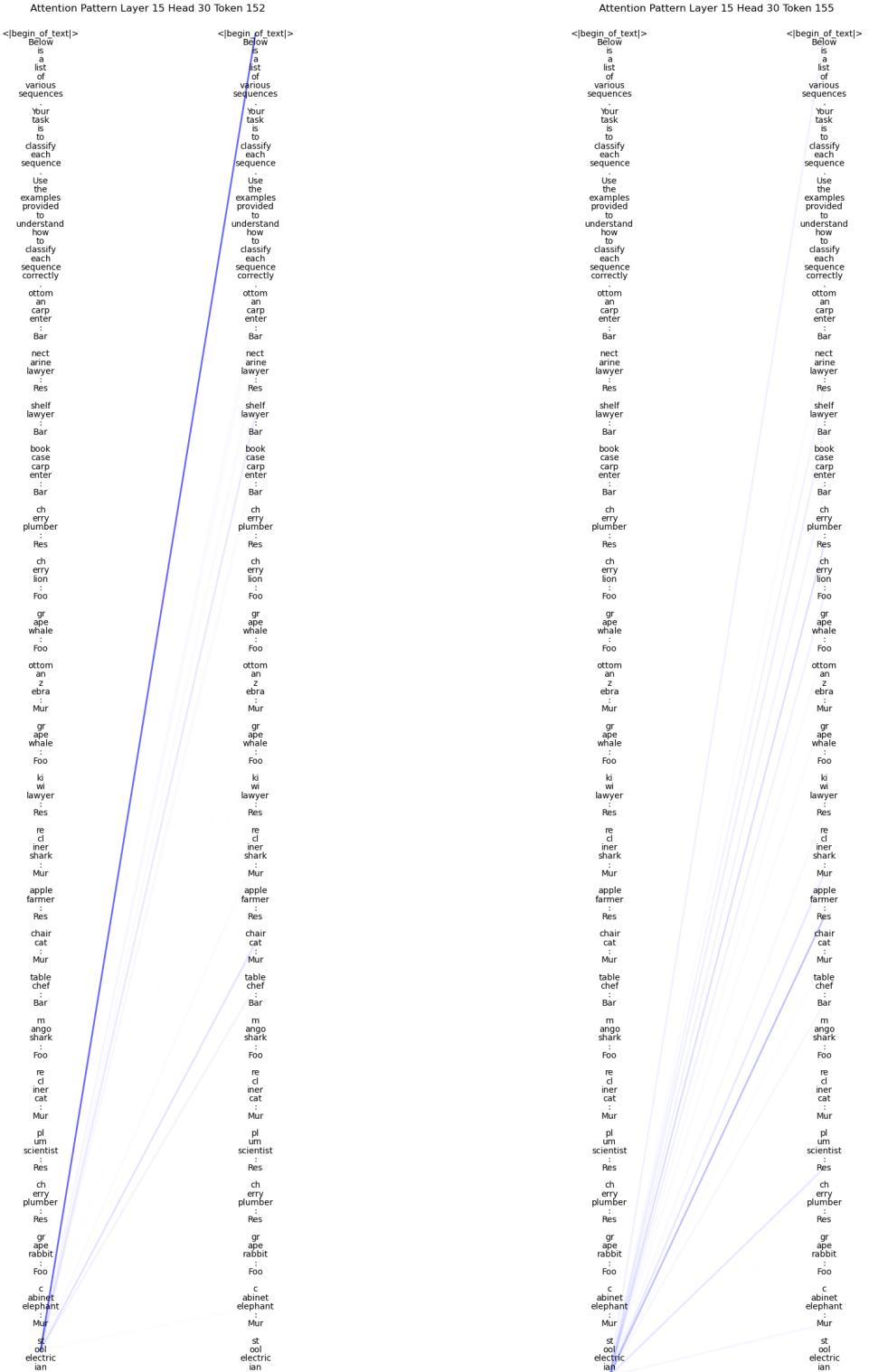


Figure 35: Attention pattern of token 152 in head 30 of layer 15 in Llama-3-8B. Example 3/5.

Figure 36: Attention pattern of token 155 in head 30 of layer 15 in Llama-3-8B. Plot 3/5.

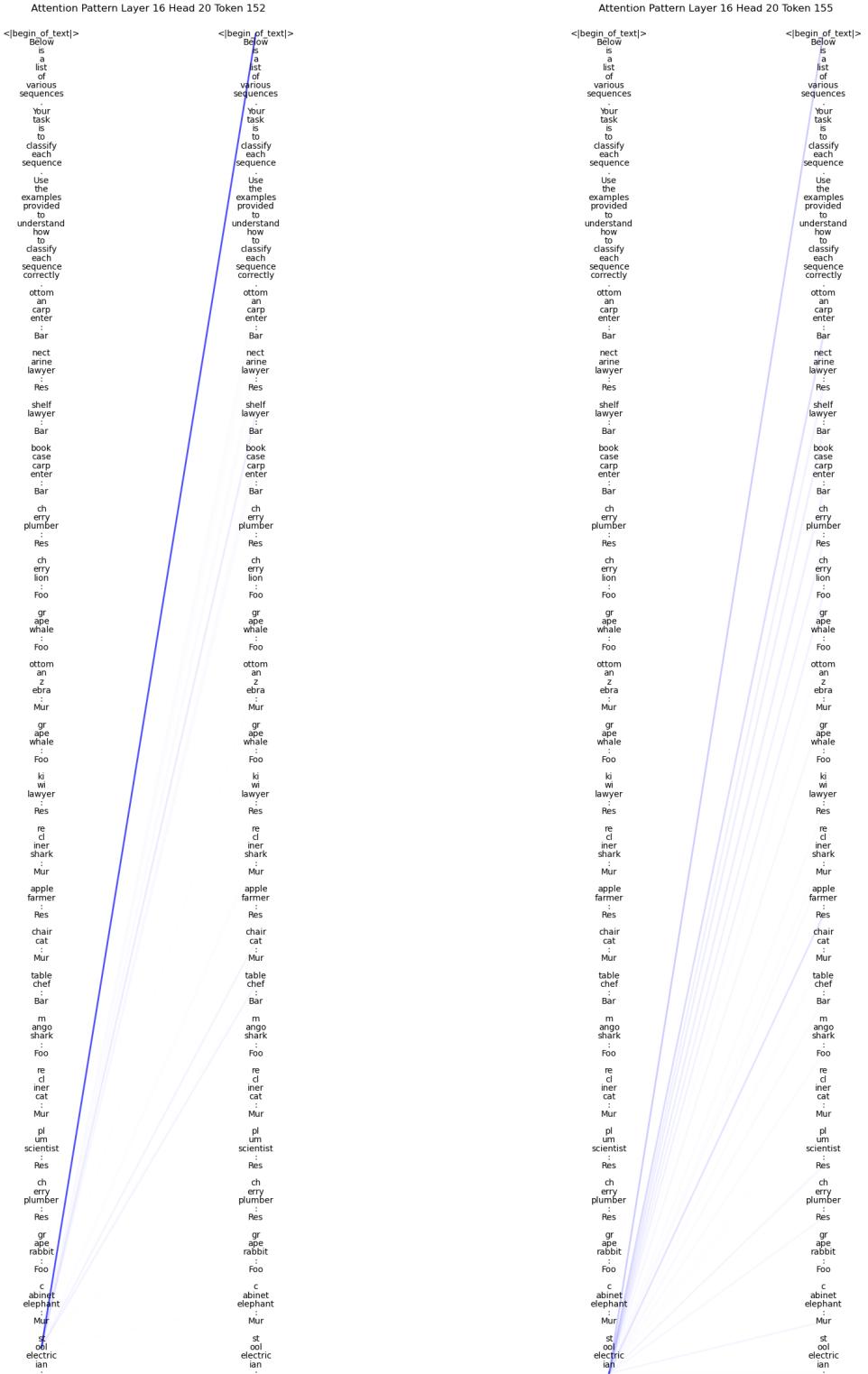


Figure 37: Attention pattern of token 152 in head 20 of layer 16 in Llama-3-8B. Example 3/5.

Figure 38: Attention pattern of token 155 in head 20 of layer 16 in Llama-3-8B. Plot 3/5.

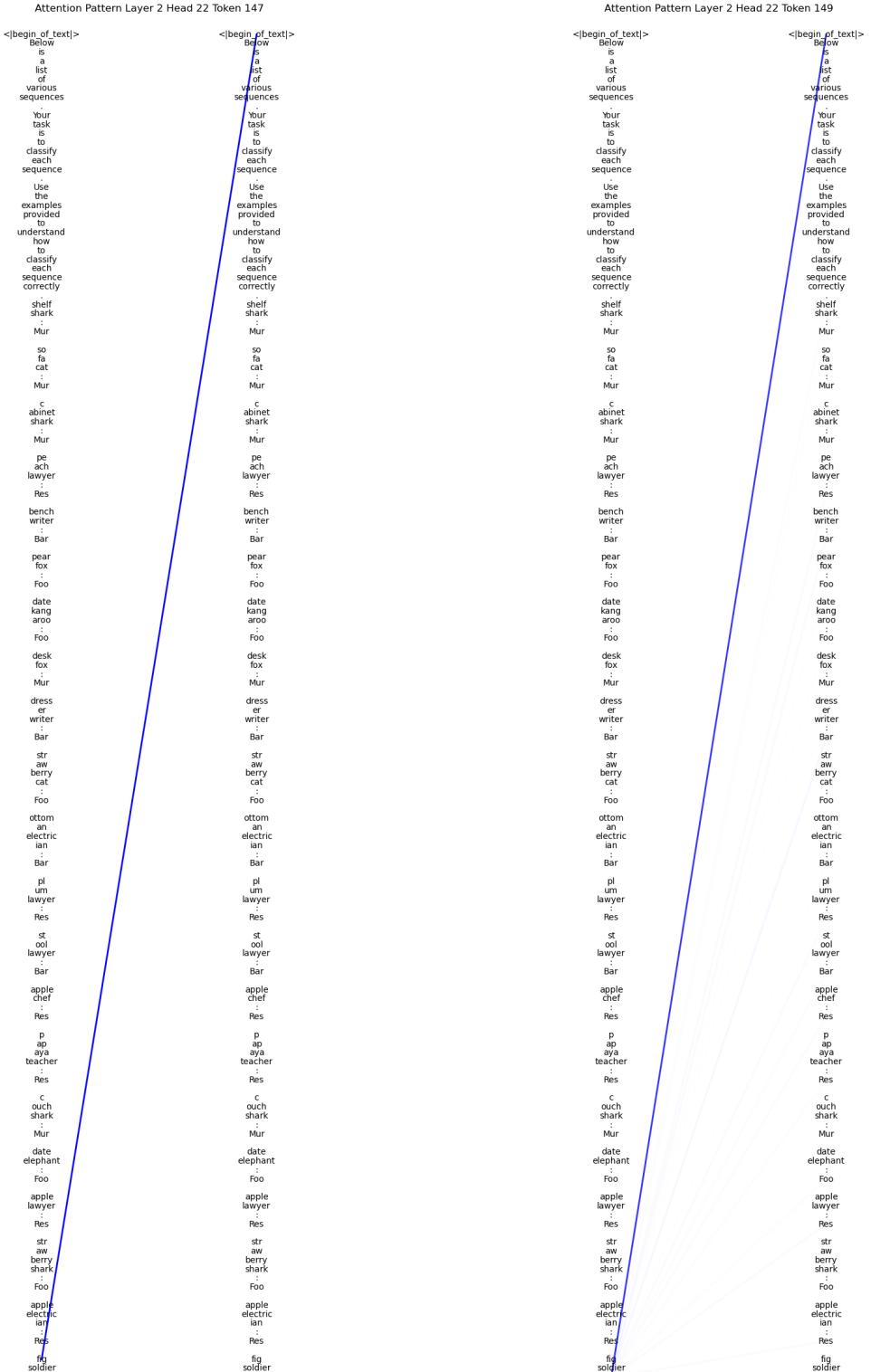


Figure 39: Attention pattern of token 147 in head 22 of layer 2 in Llama-3-8B. Example 4/5.

Figure 40: Attention pattern of token 149 in head 22 of layer 2 in Llama-3-8B. Plot 4/5.

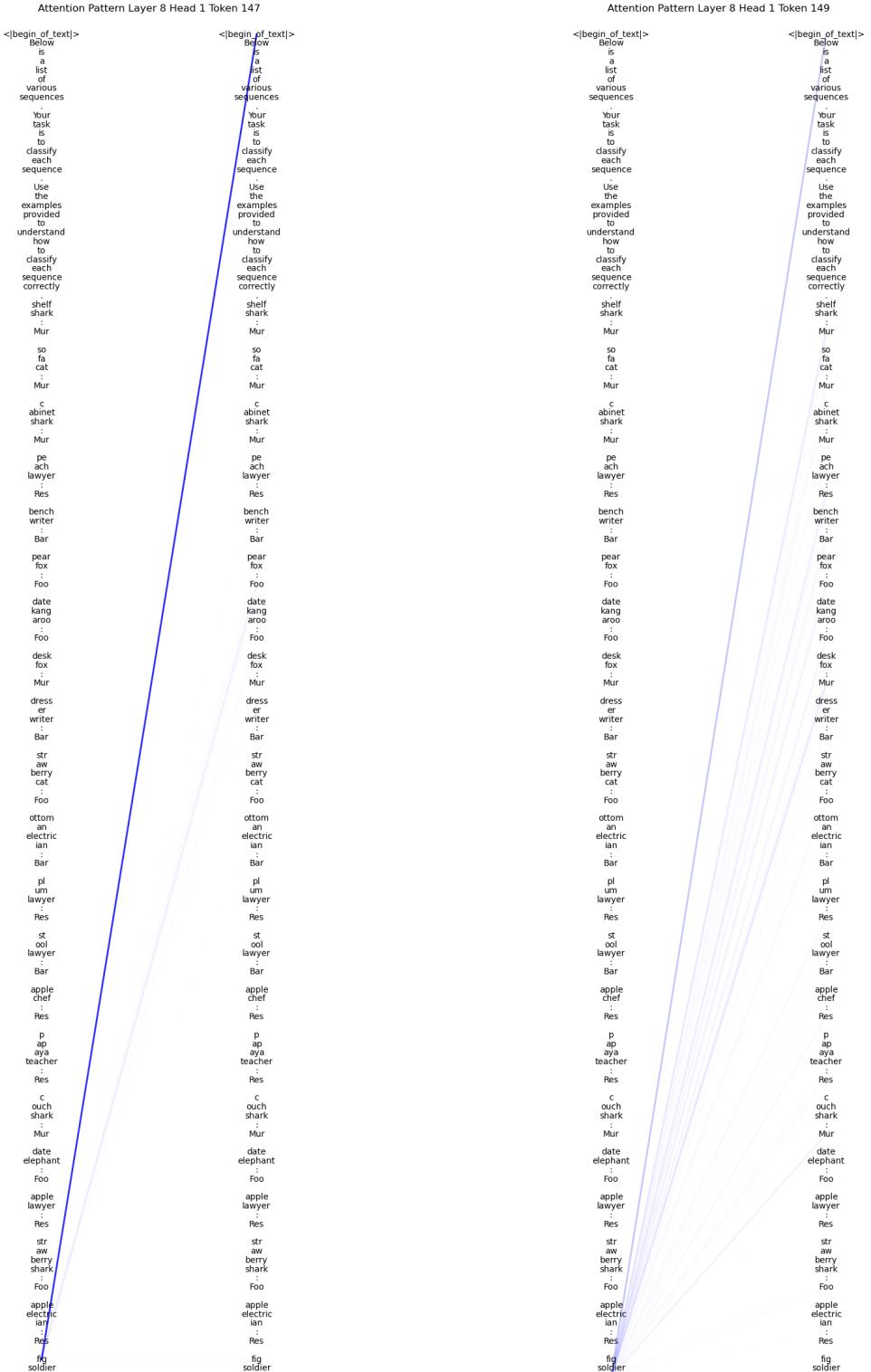


Figure 41: Attention pattern of token 147 in head 1 of layer 8 in Llama-3-8B. Example 4/5.

Figure 42: Attention pattern of token 149 in head 1 of layer 8 in Llama-3-8B. Plot 4/5.

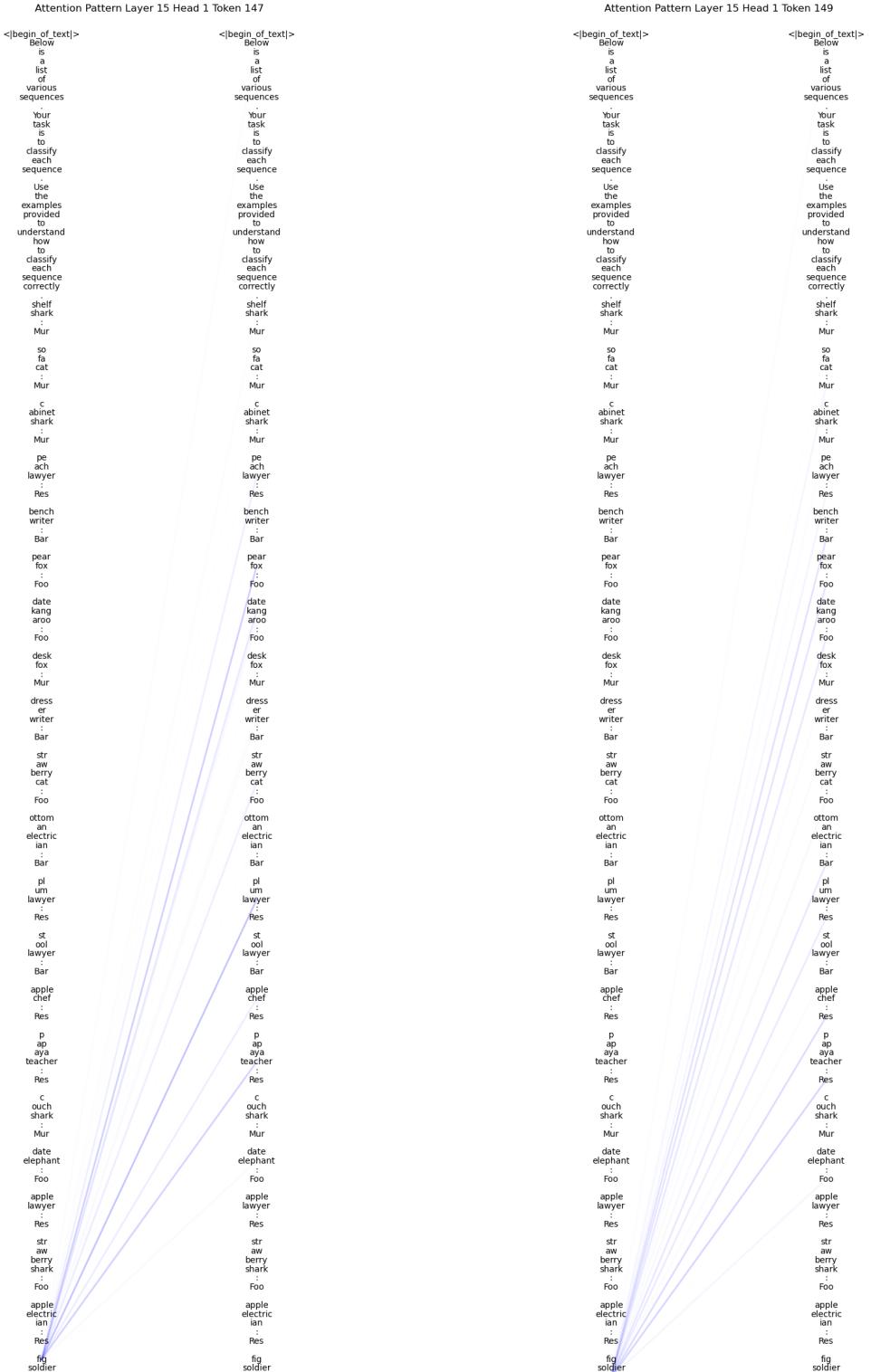


Figure 43: Attention pattern of token 147 in head 1 of layer 15 in Llama-3-8B. Example 4/5.

Figure 44: Attention pattern of token 149 in head 1 of layer 15 in Llama-3-8B. Plot 4/5.

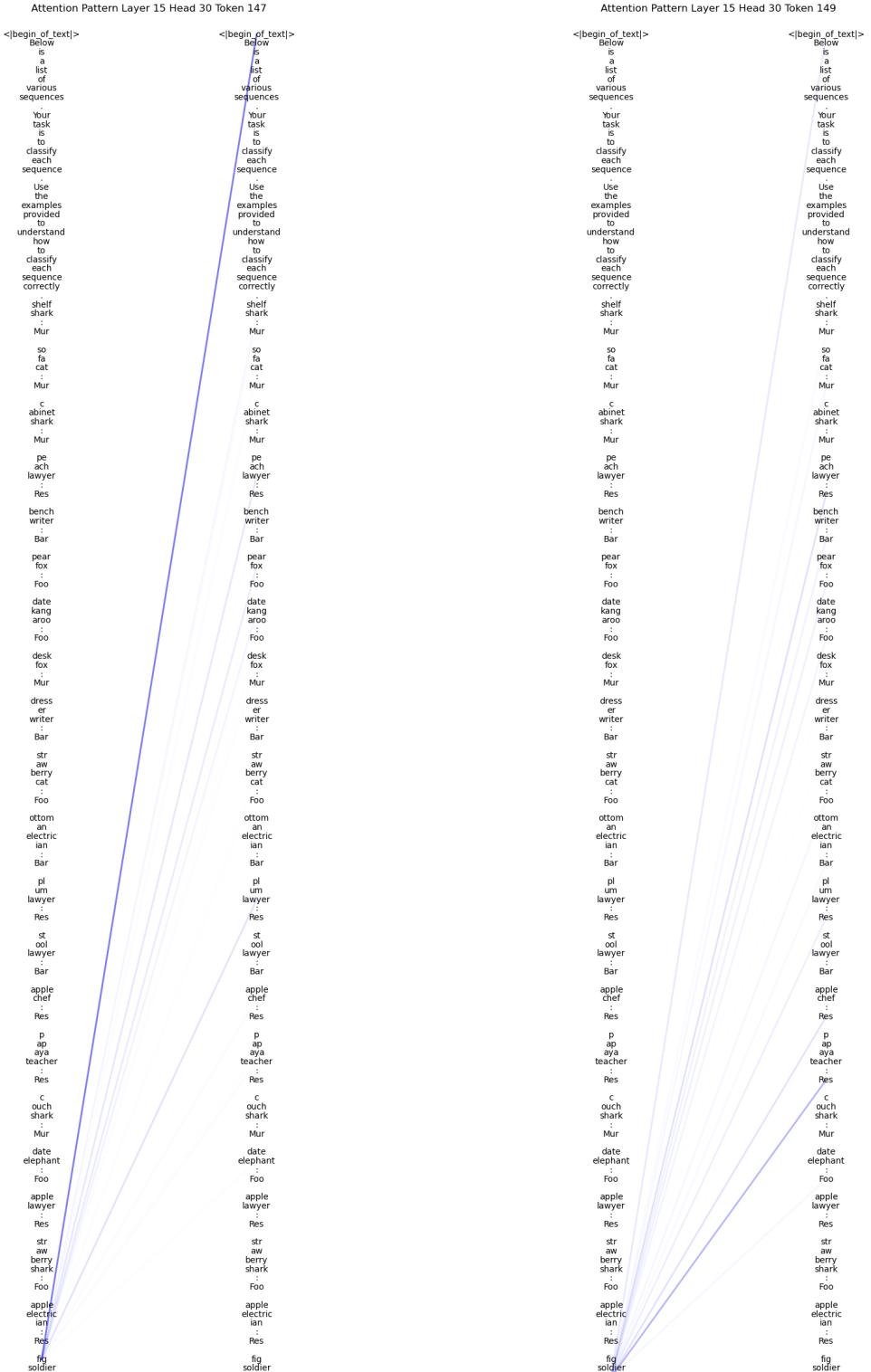


Figure 45: Attention pattern of token 147 in head 30 of layer 15 in Llama-3-8B. Example 4/5.

Figure 46: Attention pattern of token 149 in head 30 of layer 15 in Llama-3-8B. Plot 4/5.

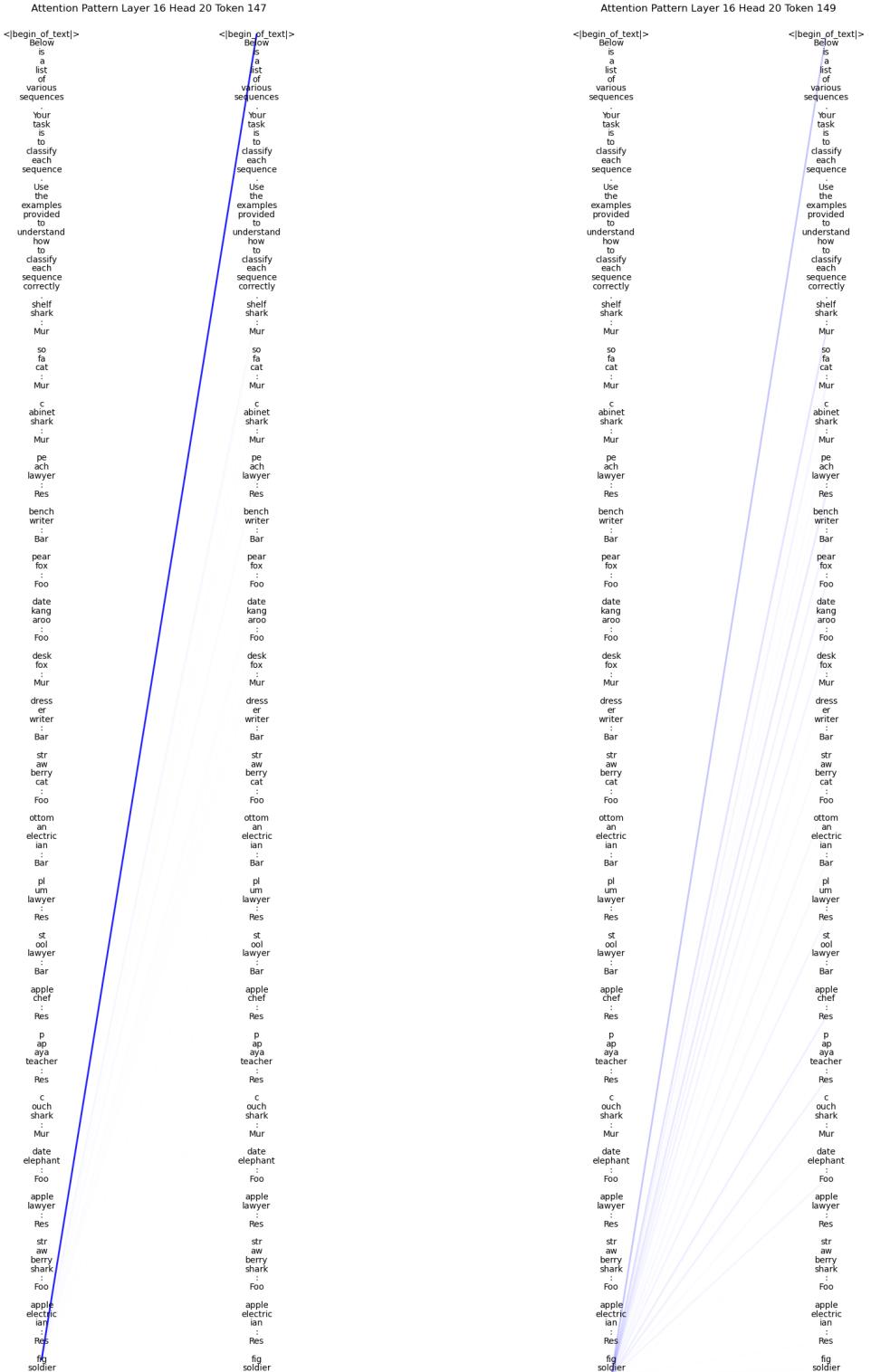


Figure 47: Attention pattern of token 147 in head 20 of layer 16 in Llama-3-8B. Example 4/5.

Figure 48: Attention pattern of token 149 in head 20 of layer 16 in Llama-3-8B. Plot 4/5.

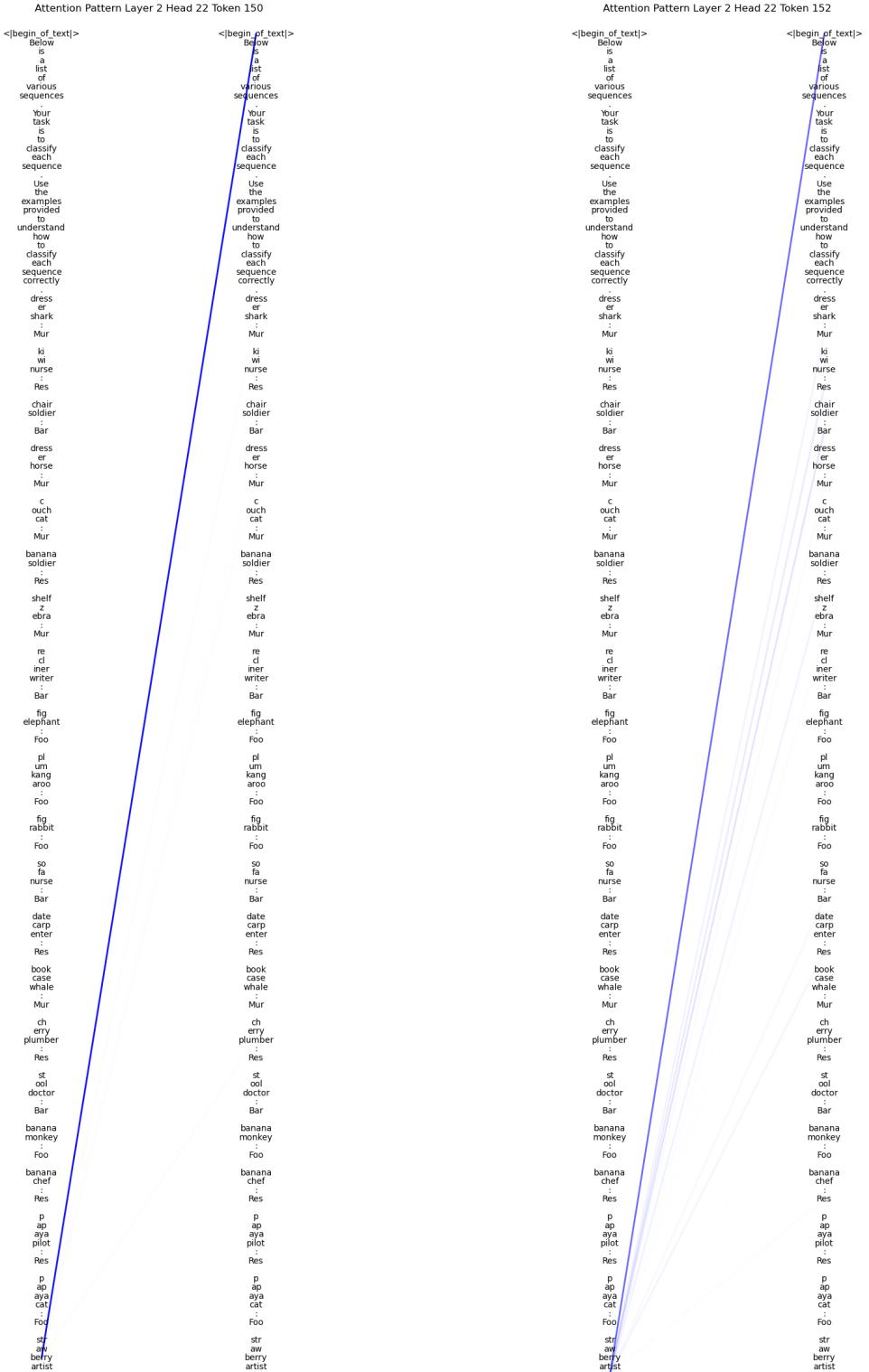


Figure 49: Attention pattern of token 150 in head 22 of layer 2 in Llama-3-8B. Example 5/5.

Figure 50: Attention pattern of token 152 in head 22 of layer 2 in Llama-3-8B. Plot 5/5.

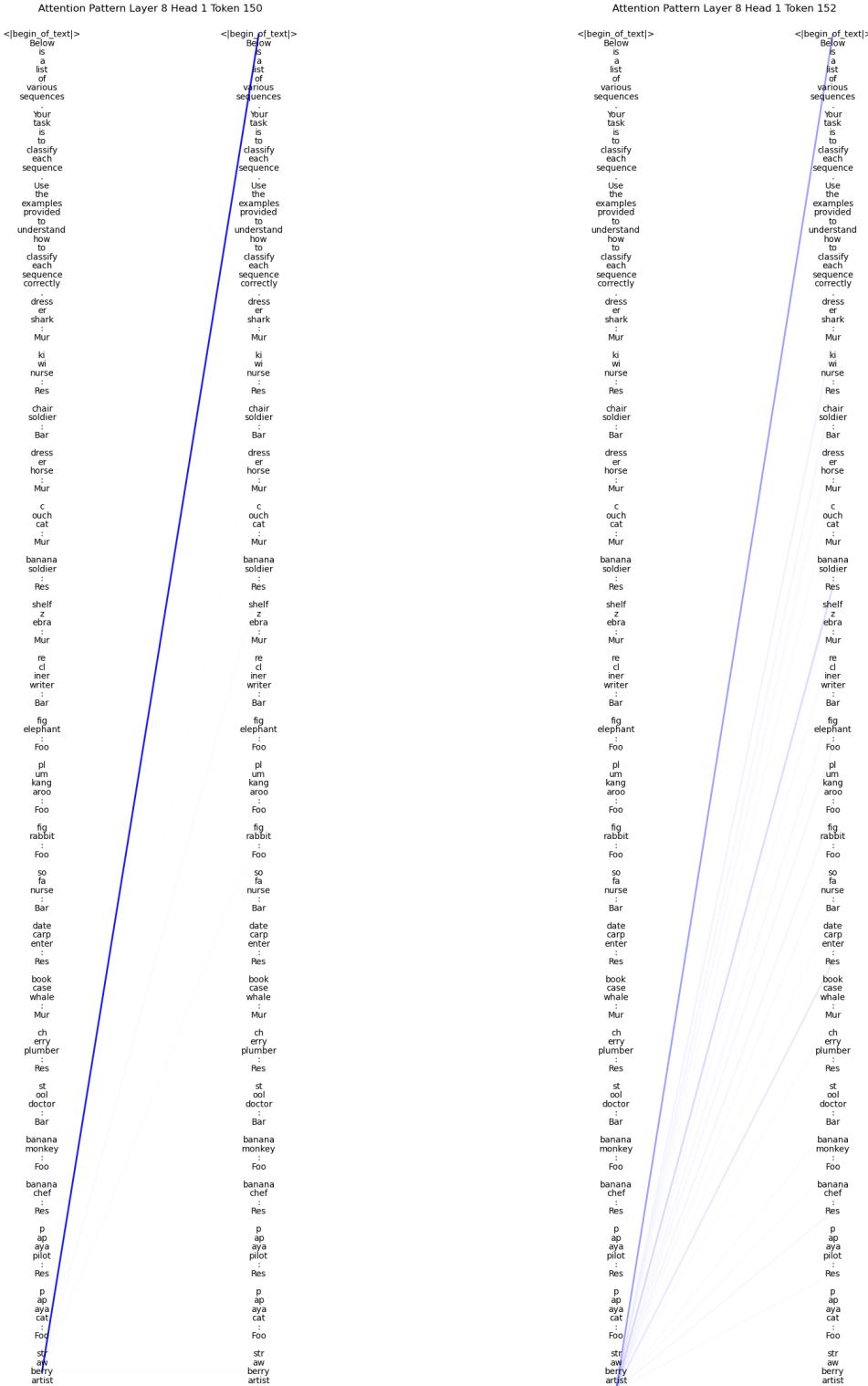


Figure 51: Attention pattern of token 150 in head 1 of layer 8 in Llama-3-8B. Example 5/5.

Figure 52: Attention pattern of token 152 in head 1 of layer 8 in Llama-3-8B. Plot 5/5.

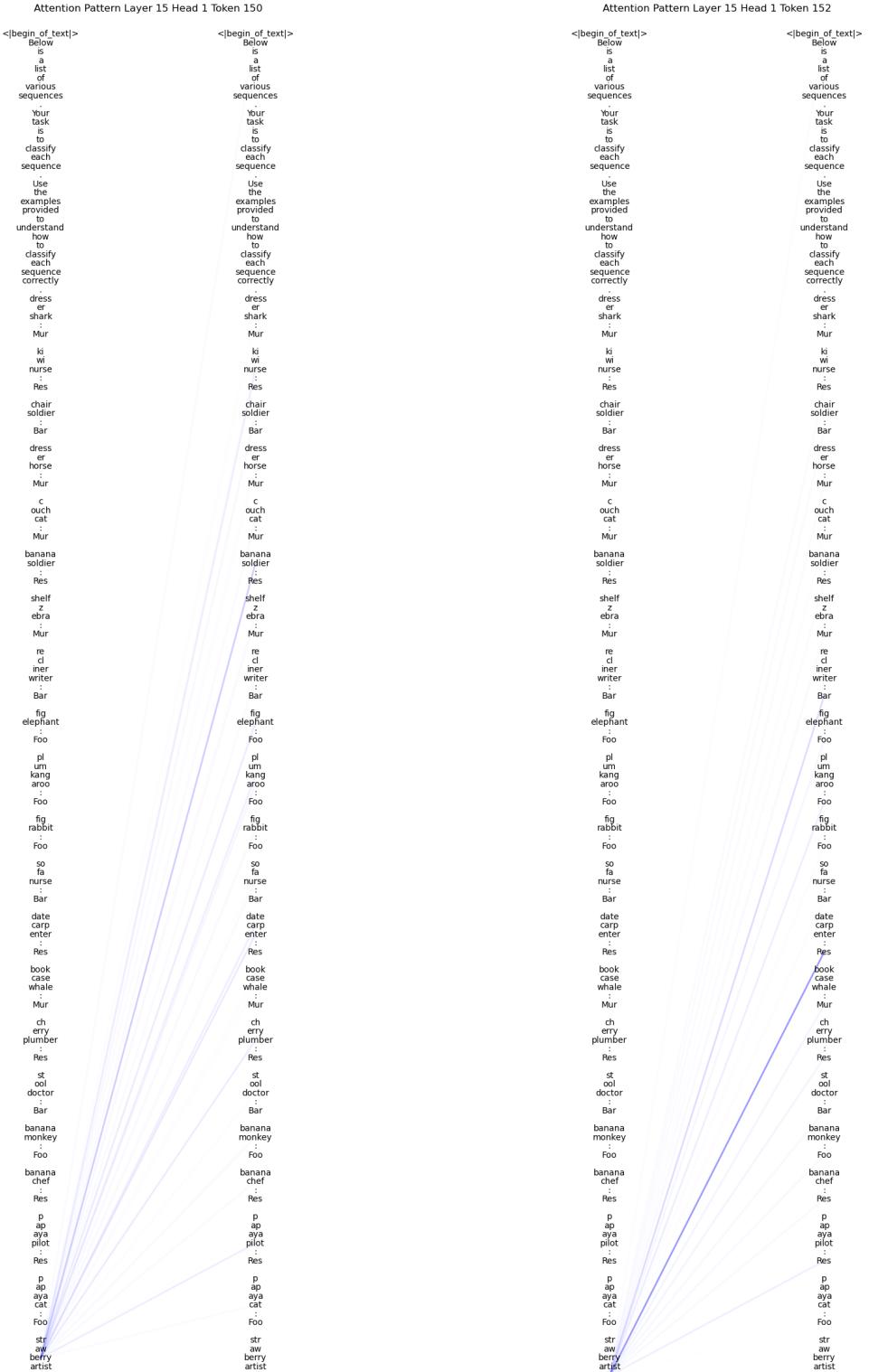


Figure 53: Attention pattern of token 150 in head 1 of layer 15 in Llama-3-8B. Example 5/5.

Figure 54: Attention pattern of token 152 in head 1 of layer 15 in Llama-3-8B. Plot 5/5.

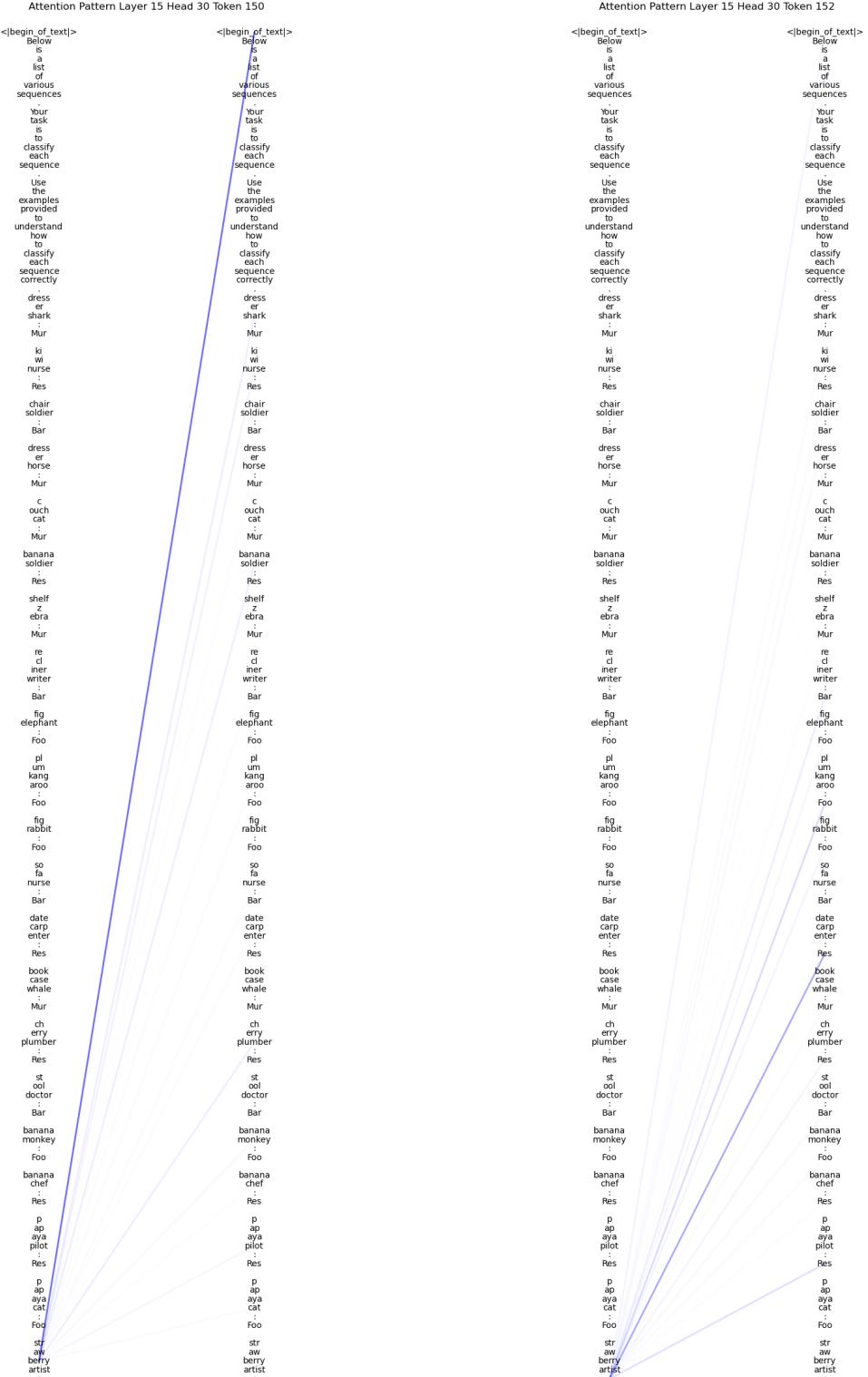


Figure 55: Attention pattern of token 150 in head 30 of layer 15 in Llama-3-8B. Example 5/5.

Figure 56: Attention pattern of token 152 in head 30 of layer 15 in Llama-3-8B. Plot 5/5.

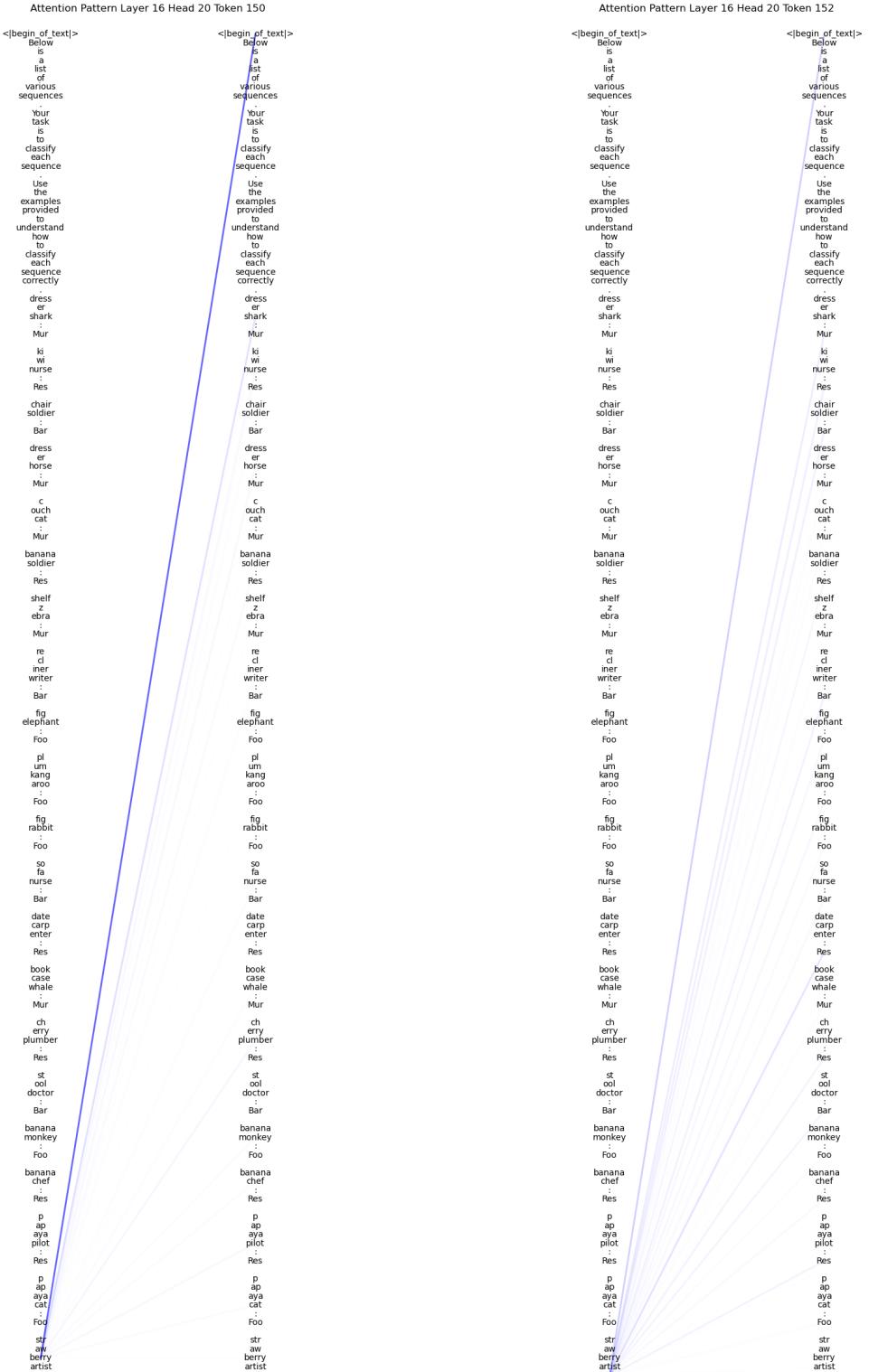


Figure 57: Attention pattern of token 150 in head 20 of layer 16 in Llama-3-8B. Example 5/5.

Figure 58: Attention pattern of token 152 in head 20 of layer 16 in Llama-3-8B. Plot 5/5.