OracleKV: Oracle Guidance for Question-Independent KV Cache Eviction

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Abstract

Key-Value (KV) caching is a widely adopted technique in large language models (LLMs) to accelerate long-context inference. While recent studies predominantly focus on question-dependent KV cache eviction where cache entries are evicted based on known queries. In this paper, however, we observe these approaches often fail in question-independent scenarios. Our empirical analysis reveals that most existing KV cache eviction methods underperform in this setting due to their heavy reliance on importance metrics derived from question tokens. The core challenge here is to conduct well-founded estimation on token importance without access to future questions. To address this, we propose OracleKV for question-independent KV cache eviction. OracleKV operates by steering model's attention with an oracle guidance containing surface-level statistics of user preferences from large-scale real-world dialogues. Unlike existing methods, OracleKV operates at the data level, allowing seamless integration with other eviction algorithms in a plug-and-play manner. We evaluate OracleKV on both multi-turn and single-turn benchmarks, demonstrating its efficiency and effectiveness.

1. Introduction

Recently, long-context capabilities have become a standard feature in large language models (LLMs)(Tang et al., 2025; Wang et al., 2025; OpenAI, 2023; Anthropic, 2024; Meta, 2025; Yang et al., 2024b). For example, GPT-4.1(Achiam et al., 2023) can process up to 1M tokens, Claude 3.7 (Anthropic, 2024) supports a 200K-token context window, and the instruction-tuned version of LLaMA-4 (Meta, 2025) extends this further to 10M tokens. These models exhibit remarkable potential on long-context tasks, achieving groundbreaking performance on various language understanding and generation benchmarks (Hendrycks et al., 2021; Bai et al., 2024; Li et al., 2023; Ghazal et al., 2013; Dong et al., 2025). However, the Key-Value (KV) cache used during inference scales linearly with sequence length, leading to substantial memory and computational overhead for long-sequence inference in LLMs (Zhang et al., 2023; Liu et al., 2024b; 2025a;b).

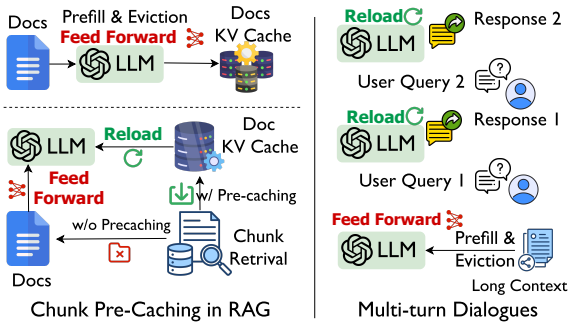

Figure 1. Question-independent KV cache eviction scenarios.

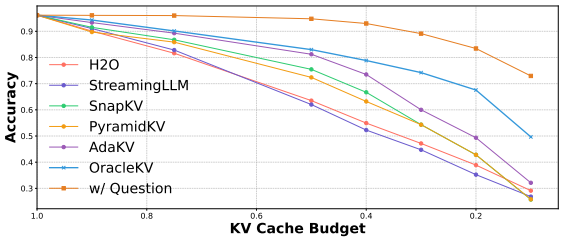

Figure 2. Question-independent KV cache eviction scenarios.

Evidence from several studies (Liu et al., 2024b; Zhang et al., 2023; Liu et al., 2025a) suggests that only a small subset of the KV cache contributes to the majority of the model's attention. As a result, many KV cache compression methods (Li et al., 2024a; Xiao et al., 2024b; Zhang et al., 2023) have been proposed, leveraging improved important metrics to identify and retain the most informative tokens. Most current KV cache selection approaches (Qin et al., 2025; Cai et al., 2024; Fu et al., 2024; Feng et al., 2024) are based on *observation window* (Li et al., 2024a) selection, which estimates the token importance based on the attention distribution of recent tokens. These methods achieve impres-

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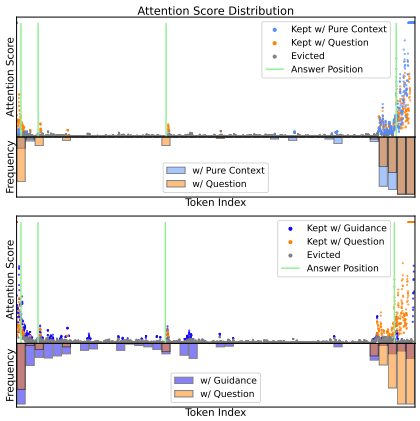

Figure 3. Visualization of attention distribution and kept KV entries (10% budget).

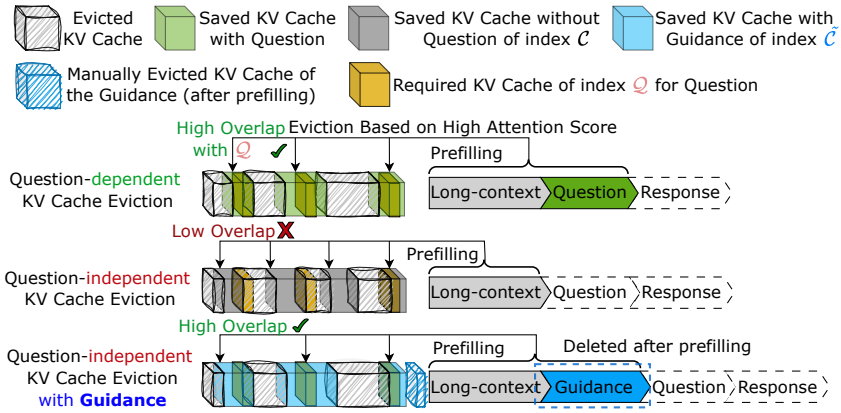

Figure 4. Overview of OracleKV. The KV entries of the context are evicted based on the attention score with oracle guidance.

sive results on several well-established benchmarks (such as Longbench (Bai et al., 2024)). However, in question-independent scenarios where question is unknown, such as chunks pre-caching in RAG (Yao et al., 2025) and multi-turn dialogues (Li et al., 2024b) as in Figure 1, we observe their significant performance drop in Figure 2.

Our empirical analysis in Figure 3 reveals that the accurate KV entry selection heavily rely on the attention distribution induced by question tokens, which leads to the inadaptability in the question-independent scenarios. Thus, the fundamental challenge of this scenario lies in conducting well-founded token importance estimation without query.

To bridge this gap, we propose to find some alternatives to the exact future questions, which help estimate token importance. Inspired by recent reports (Handa et al., 2025; Maslej et al., 2025) on large-scale user dialogues with LLMs, we introduce a method called **OracleKV**. At a high level, we append a *oracle guidance* to the end of the long context as a substitute of the exact question. This guidance encodes the surface-level statistics about the distribution of future questions—such as the expected types of queries and categories of relevant information—based on prior analyses (Handa et al., 2025; Maslej et al., 2025). During inference, we estimate the importance of each context token by measuring its relevance with this oracle guidance. Tokens with low correspondence to the anticipated question distribution are progressively evicted until the retained KV cache fits the memory budget.

In contrast to prior approaches that rely on token retention heuristics based on internal model-specific computational characteristics (Li et al., 2024a; Feng et al., 2024; Xiao et al., 2024a), OracleKV leverages external statistical priors about likely information requirements at the data level. This design makes it highly flexible and model-agnostic: OracleKV can be seamlessly integrated with existing KV cache compression frameworks to enhance their performance, especially under question-independent scenarios.

2. OracleKV

2.1. An Information Retaining Perspective of KV Cache

In this section, we investigate how an LLM can answer a question from the perspective of *retaining* information, even when only a subset of cache entries is preserved. We visualize the attention distribution induced by pure context and the query in Figure 11, which reveals that accuracy degradation primarily results from a mismatch between: (1) the KV cache entries retained by a given eviction algorithm, and (2) the entries actually required to answer the question, as measured by their position and relevance with the question.

2.2. Attention Manipulation via Data-level Intervention

We aim to steer the distribution of attention across semantic types in the retained entries. We resort to recent studies (Handa et al., 2025; Maslej et al., 2025) that indicates users exhibit distinct preferences across task types when interacting with large language models (LLMs). We summarize the dominant information types associated with common long-context tasks from (Handa et al., 2025; Maslej et al., 2025) and propose a data-level intervention method to manipulate attention distribution. An overview of our method is presented in Fig.4. We begin by manually designing an oracle guidance $\tilde{\mathcal{O}}$ of length L_o, which encodes surface statistics of prevalent information types in large-scale dialogues (Handa et al., 2025; Maslej et al., 2025). This oracle guidance $\tilde{\mathcal{O}}$ is then appended to the input context $\mathbf{X}_{\text{ctx}}$ as a substitude of $\mathbf{X}_{\text{ques}}$ (question), allowing it to steer the attention distribution during the prefilling phase:

$$\mathbf{K} = \mathbf{W}_K \text{Concat}(\mathbf{X}_{\text{ctx}}, \tilde{\mathcal{O}}), \quad \mathbf{V} = \mathbf{W}_V \text{Concat}(\mathbf{X}_{\text{ctx}}, \tilde{\mathcal{O}}). \tag{1}$$

Following the instruction format described in (Zhou et al., 2023), we design $\tilde{\mathcal{O}}$ to encourage the model to assign higher attention to tokens representing specific information types. We provide specific examples of $\tilde{\mathcal{O}}$ in Appendix. Our goal is to select the KV entries semantically correlated to the oracle $\tilde{\mathcal{O}}$. Then we focus on the attention scores within the cache

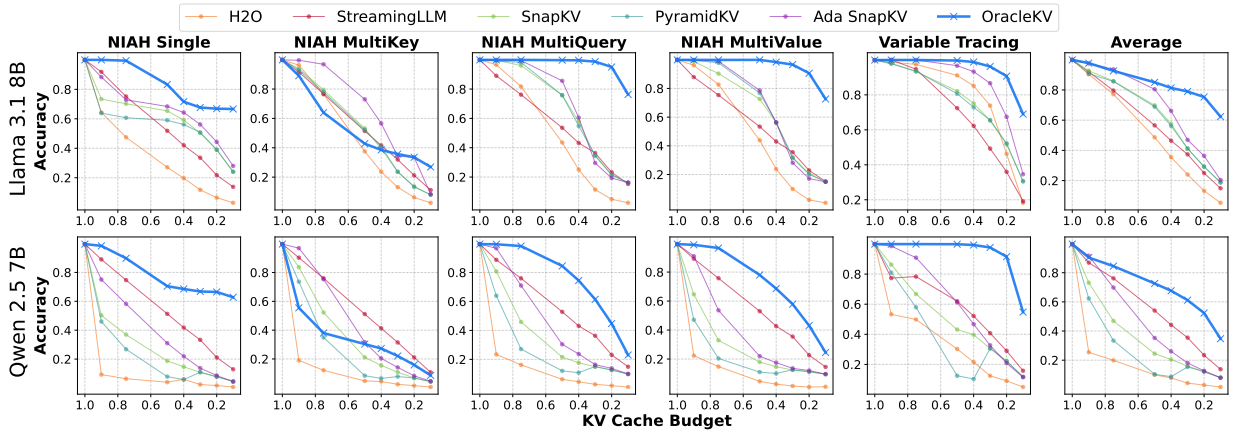

Figure 5. Performance comparison on RULER (Hsieh et al., 2024) benchmark. OracleKV provides superior tradeoff.

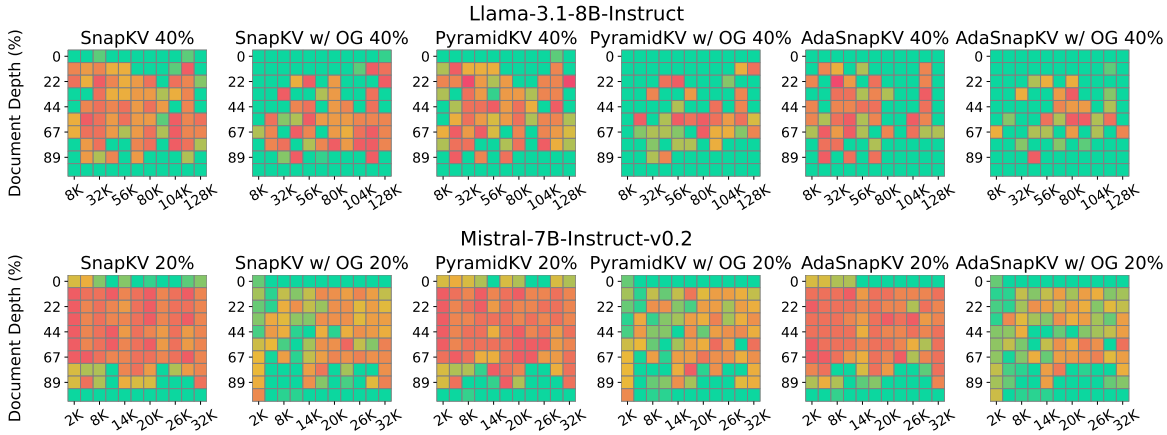

Figure 6. Oracle Guidance provides significant performance increase on the Needle-In-A-Haystack (Kamradt, 2023) pressure test while integrating into uniform (SnapKV(Li et al., 2024a)), layer-wise (PyramidKV (Cai et al., 2024)) and head-wise (Ada SnapKV (Feng et al., 2024)) budget allocation methods.

entry window of $\tilde{\mathcal{O}}$, as illustrated in Fig. 13, and retain the top B entries using the following criterion:

$$\arg\max_{\mathcal{C}} \sum_{i=L-L_o}^{L} \mathbf{A}[i, : -L_o], \quad \text{s.t. } |\mathcal{C}| = B. \tag{2}$$

Finally, we manually exclude the KV entries corresponding to $\tilde{\mathcal{O}}$ itself, as these surface statistics do not directly contribute to answering the question.

3. Experiment

Settings. We evaluate OracleKV with several benchmarks, including Longbench (Bai et al., 2024), RULER (Hsieh et al., 2024), Needle-In-A-Haystack (Kamradt, 2023), and SCBench (Li et al., 2024b). We employ three open-source LLMs: Mistral-7B-Instruct-v0.2, Llama-3.1-8B-Instruct, and Qwen2.5-7B-Instruct. We compare OracleKV against several strong baselines, including StreamingLLM (Xiao et al., 2024b), H2O (Zhang et al., 2023), SnapKV (Li et al., 2024a), PyramidKV (Cai et al., 2024), DuoAttention (Xiao et al., 2024a) and AdaKV (Feng et al., 2024).

3.1. Accuracy Evaluation

LongBench(Bai et al., 2024). Table 1 presents the performance of various methods across five task types, encompassing 14 datasets. OracleKV consistently demonstrates superior performance on most tasks. Notably, under a 10% cache budget, OracleKV and its variant significantly outperforms other methods across solid most of tasks on LLama 3.1, achieving an average improvement of 6.7%, highlighting its superior adaptability under extreme memory constraints.

RULER(Hsieh et al., 2024). Figure 5 illustrates the performance across five retrieval subtasks, comparing baselines with KV budgets ranging from 100% to 10%. OracleKV demonstrates an exceptional tradeoff between memory budget and accuracy across most subtasks, highlighting its strong retrieval capabilities. Notably, OracleKV experiences a minimal performance drop on three subtasks with only 30% of the KV budget.

Needle-In-A-Haystack (NIAH)(Kamradt, 2023). As shown in Figure6, baseline methods demonstrate significant improvement when integrated with Oracle Guidance,

Table 1. Average performance of various baselines across different LLMs in single-turn (Bai et al., 2024) and multi-turn (Li et al., 2024b) benchmarks. We compare OracleKV with baselines under 40% and 10% KV budget.

Method	Budget	Single-turn LongBench						Multi-turn SCBench						
		Sin.QA	Mul.QA	Sum.	Few.Shot.	Syn.	AVG.	M.C.	M.S.	M.F.	QA.En	QA.Ch	Sum.	AVG.
LLaMA-3.1-8B-Instruct														
Full Cache	100%	44.3	47.0	29.2	51.1	55.6	45.7	5.7	40.0	28.0	20.9	27.5	30.9	25.8
StreamingLLM	40%	27.9	34.6	25.7	53.4	26.1	33.5	7.9	38.2	12.2	18.0	16.3	22.3	19.1
SnapKV		35.3	44.8	26.5	53.6	54.5	42.9	6.1	**44.4**	22.5	17.8	23.5	27.7	23.7
PyramidKV		34.1	35.3	25.7	**55.3**	51.5	40.4	5.5	42.8	19.5	18.6	19.9	23.5	21.6
Ada SnapKV		37.0	45.6	26.7	55.1	54.3	44.1	5.7	40.4	19.8	19.3	24.0	28.3	22.9
DuoAttention		**42.4**	44.3	27.2	53.5	52.8	43.5	**8.3**	39.6	15.3	18.6	25.4	29.4	22.8
OracleKV		40.9	**46.4**	27.4	54.0	**56.1**	**45.0**	5.2	44.2	**23.3**	**20.5**	25.7	29.8	24.8
Ada OracleKV		42.0	45.5	**27.6**	53.4	55.8	44.9	5.7	43.0	22.9	**20.5**	**27.2**	**30.5**	**24.9**
StreamingLLM	10%	20.7	24.6	21.3	51.0	10.0	25.5	6.6	38.9	12.0	15.6	10.1	20.8	17.3
SnapKV		22.6	29.6	21.7	51.6	29.5	30.1	6.1	**50.7**	21.2	15.2	14.5	22.3	21.7
PyramidKV		21.3	24.0	21.7	51.8	27.1	29.2	5.2	48.8	20.6	13.6	11.0	21.4	20.1
Ada SnapKV		24.1	30.7	22.3	51.7	31.5	32.1	5.7	50.4	20.3	14.7	15.9	23.0	21.7
DuoAttention		18.2	23.3	21.4	49.4	28.0	28.1	**7.4**	47.4	19.7	12.3	7.6	25.3	20.0
OracleKV		24.5	33.2	23.5	56.3	45.3	36.5	6.1	45.2	**21.3**	**18.5**	18.1	25.9	22.5
Ada OracleKV		**28.8**	**34.0**	**23.8**	**58.3**	**49.3**	**38.8**	5.7	50.4	21.0	17.0	**19.3**	**26.3**	**23.3**

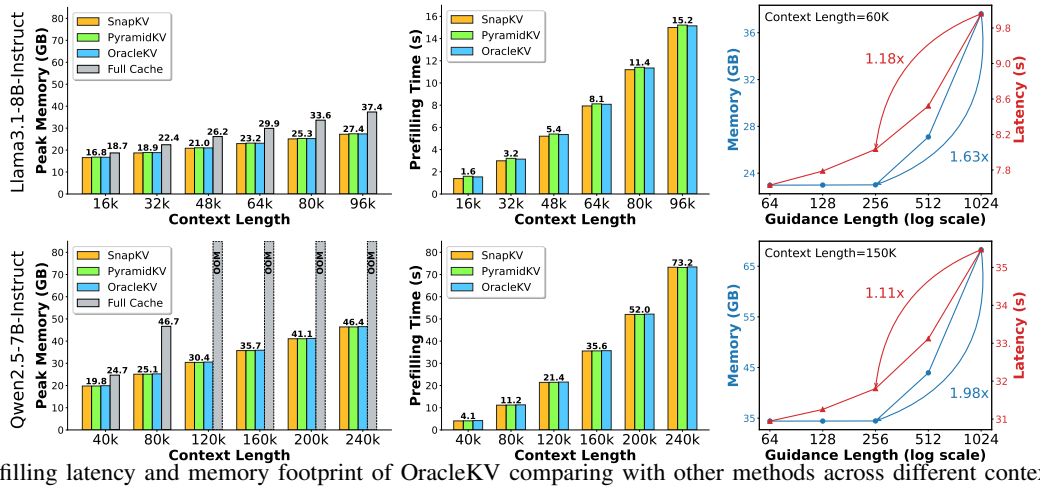

Figure 7. Prefilling latency and memory footprint of OracleKV comparing with other methods across different context length: (1) Comparison of peak memory usage. (2) Comparison of prefilling latency. (3) The computation cost scales with the length of the guidance.

highlighting its effectiveness in refining retrieval accuracy.

Multi-turn Benchmark. We evaluate OracleKV along with all baselines on the multi-turn SCBench(Li et al., 2024b). Table1 shows that OracleKV consistently outperforms all other baselines on most tasks, maintaining superior performance under the same KV budget across all three models.

3.2. Efficiency Evaluation

We evaluate the prefilling latency and memory footprint of OracleKV on Llama-3.1-8B-Instruct for 96K context prefilling and Qwen2.5-7B-Instruct for 240K context prefilling.

Peak Memory Usage. As shown in 7(1), OracleKV shows comparable memory savings with uniform budget allocation strategies (SnapKV (Li et al., 2024a)) and layer-pattern budget allocation strategies (PyramidKV (Cai et al., 2024)), notably reducing memory consumption of full attention.

Prefilling Latency (Time-To-First-Token). Figure 7(2) shows OracleKV achieves comparable TTFT to PyramidKV (fixed-pattern allocation) and SnapKV (uniform allocation).

Computational Cost with Guidance Length. We examine how memory footprint and prefilling latency scale with the guidance length, using context lengths of 64K and 150K. As shown in Figure 7(3), the memory usage and latency increases to 1.63× and 1.18× from length of 256 to 1K.

3.3. Ablation Study

We perform ablation studies on the multi-key retrieval and summarization tasks to investigate the effect of various design choices in OracleKV. Results are provided in Appendix.

4. Conclusion

We present OracleKV, a data-level intervention approach designed for question-independent KV cache compression. OracleKV steers the attention distribution of by appending an oracle guidance to the pure context, then selects semantically correlated KV entries based on corresponding attention score. We confirm the effectiveness of OracleKV and hope it could serve as an useful component within more comprehensive long-context inference framework.

Impact Statement

OracleKV provides a new perspective to guide KV cache eviction in large language models (LLMs) by leveraging data-level intervention to introduce inductive biases. While OracleKV demonstrates significant performance improvements in question-independent eviction settings, its potential extension to other setting (such as question-aware or task-oriented KV cache eviction) presents a exciting direction for future research. Additionally, the limitations of OracleKV, especially the task-specific nature of its benefits and the increased computational and memory overhead, highlight important trade-offs in the practical deployment. In particular, the increased latency and memory consumption could pose challenges for real-time applications on resource-constrained devices.

Furthermore, the need for task-specific oracle design raises concerns about scalability and generalizability, potentially reinforcing disparities between well-resourced and low-resource tasks or domains. We believe that future work should explore more efficient and generalizable oracle guidance designs that balance interpretability, performance, and system efficiency, ensuring that such techniques can be equitably applied across a broad range of use cases.

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A. Introduction

Recently, long-context capabilities have become a standard feature in large language models (LLMs)(OpenAI, 2023; Anthropic, 2024; Meta, 2024; 2025; Yang et al., 2024b; Achiam et al., 2023). For example, GPT-4.1(OpenAI, 2023; Achiam et al., 2023) can process up to 1M tokens, Claude 3.7 (Anthropic, 2024) supports a 200K-token context window, and the instruction-tuned version of LLaMA-4 (Meta, 2025) extends this further to 10M tokens. These models exhibit remarkable potential on long-context tasks, achieving groundbreaking performance on various language understanding and generation benchmarks (Hendrycks et al., 2021; Bai et al., 2024; Li et al., 2023; Ghazal et al., 2013). However, the Key-Value (KV) cache used during inference scales linearly with both sequence length and batch size, leading to substantial memory and computational overhead for long-sequence inference in LLMs (Zhang et al., 2023; Liu et al., 2024b).

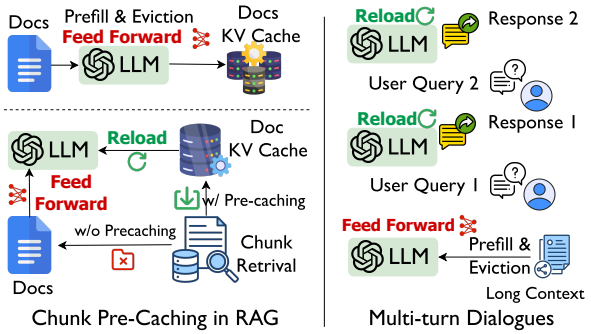

Figure 8. Question-independent KV cache eviction scenarios.

Evidence from several studies (Liu et al., 2024b; Zhang et al., 2023; Mu et al., 2023) suggests that only a small subset of the KV cache contributes to the majority of the model's attention. As a result, many KV cache compression methods (Li et al., 2024a; Xiao et al., 2024b; Zhang et al., 2023) have been proposed, leveraging improved important metrics to identify and retain the most informative tokens. Most current KV cache selection approaches (Qin et al., 2025; Cai et al., 2024; Fu et al., 2024; Feng et al., 2024) are based on *observation window* (Li et al., 2024a) selection, which estimates the token importance based on the attention distribution of recent tokens. These methods achieve impressive results on several well-established benchmarks (such as Longbench (Bai et al., 2024)). However, in question-independent scenarios where question is unknown, such as chunks pre-caching in RAG (Yao et al., 2025) and multi-turn dialogues (Li et al., 2024b) as in Figure 8, we observe their significant performance drop in Figure 9. This motivates the following core questions:

Why question-independent KV cache compression fails, and how to improve it?

To answer these questions, our empirical analysis in Figure 11 reveals that the accurate KV entry selection heavily rely on the attention distribution induced by question tokens, which leads to the inadaptability in the question-independent scenarios. Thus, the fundamental challenge of this scenario lies in conducting well-founded estimation of token importance in the absence of target knowledge, *i.e.* without knowing exact questions or prompts the model will respond to, as shown in Figure 10.

To bridge this gap, we propose to find some alternatives to the exact future questions, which help estimate token importance. Recent report (Handa et al., 2025; Maslej et al., 2025) on AI economics observe that in large-scale real user dialogues with LLMs, user-asked question types exhibit strong statistical regularities. Moreover, for each type of question, the associated required information follows predictable distributional patterns (Maslej et al., 2025). Inspired by this, we introduce a method called **OracleKV**. At a high level, we append a *oracle guidance* to the end of the long context as a substitute of the exact question. This guidance encodes the surface-level statistics about the distribution of future questions—such as the expected types of queries and categories of relevant information—based on prior analyses (Handa et al., 2025; Maslej et al., 2025) and large-scale benchmarks (Hendrycks et al., 2021; Rein et al., 2024; Chen et al., 2021). During inference, we estimate the importance of each context token by measuring its relevance with this oracle guidance. Tokens with low correspondence to the anticipated question distribution are progressively evicted until the retained KV cache fits the memory budget.

In contrast to prior approaches that rely on token retention heuristics based on internal model-specific computational characteristics (Li et al., 2024a; Feng et al., 2024; Xiao et al., 2024a; Cai et al., 2024; Fu et al., 2024), OracleKV leverages external statistical priors about likely information requirements at the data level. This design makes it highly flexible and model-agnostic: OracleKV can be seamlessly integrated with existing KV cache compression frameworks to enhance their performance, especially under question-independent scenarios.

This paper makes following principal contributions. (1) We identify the root cause of challenges of question-independent KV cache compression (Section C and D.1); (2) We build a theoretical model statistically illustrating the relationship between

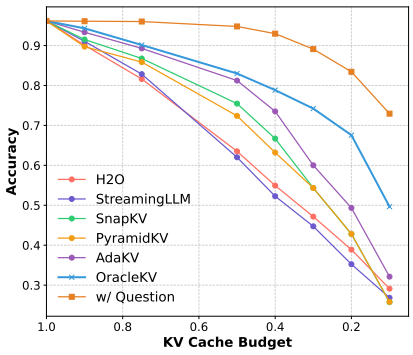

Figure 9. Accuracy of KV eviction methods without question.

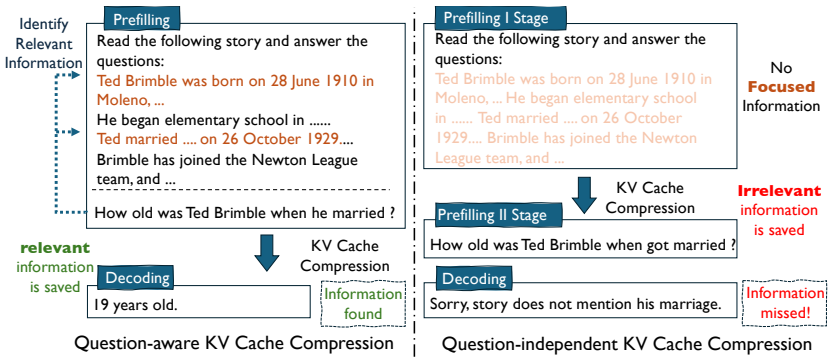

Figure 10. Question-aware KV cache compression vs. question-independent KV cache cache compression.

information induced by the question and required information to answer the question ((Section D.1). Then, we present a data-level intervention technique, OracleKV, designed to address question-independent KV cache eviction (Section D.2).(3) Our empirical evaluation shows that OracleKV results in a significant performance increase under the question-independent setting, on both single-turn long-context tasks (e.g., RAG-style pre-caching) and multi-turn dialogue scenarios, suggesting that OracleKV introduces a useful inductive bias. (Section E).

B. Related Work

KV Cache Eviction. Leveraging the inherent sparsity in the self-attention mechanisms, early studies (Liu et al., 2024b; Zhang et al., 2023) propose maintaining a queue with a pre-allocated budget and progressively evicting unimportant cache entries during the inference. StreamingLLM (Xiao et al., 2024b) and LM-Infinite (Han et al., 2024) utilize the *attention sink* phenomenon to retain both initial and most recent tokens. SnapKV (Li et al., 2024a) uses attention scores with recent tokens to estimate importance. PyramidKV (Cai et al., 2024), PyramidInfer (Yang et al., 2024c) and CAKE (Qin et al., 2025) dynamically adjust KV cache retaining ratio of different layers. DuoAttention (Xiao et al., 2024a) employs a learning-based method to identify *compression-insensitive* attention heads, while HeadKV (Fu et al., 2024) classifies heads based on their retrieval and reasoning utility. However, most existing methods (*e.g.* (Li et al., 2024a; Cai et al., 2024; Yang et al., 2024c; Qin et al., 2025; Feng et al., 2024; Fu et al., 2024; Hao et al., 2025)) rely heavily on importance metrics derived from the attention scores with given the exact question, limiting their robustness and applicability in real-world question-independent scenarios. In contrast, our approach operates at the data level, leveraging surface-level statistical regularities in the question distribution, making it compatible with existing methods and easily integrable into a broader range of applications.

In-Context Learning/Instruction Following. Early studies (Devlin et al., 2019; Liu et al., 2019) observed that language models can "learn" to perform a task from a few shot input-output examples provided in context at inference. (Xie et al., 2021) interprets the emergence of in-context learning by inferring the shared latent concept among demonstration examples. Based on these, OracleKV affects the attention behavior through in-context data manipulation, aiming to select instruction-correlated tokens.

Recent Works. Several recent works evaluate the importance of KV entries without the question. (Feng et al., 2025) identify the value states within KV entries are critical, isolated with the attention matrices. However, their approach stem from predictive perturbation analysis and do not focus on the question-independent scenarios. KV-Distill (Chari et al., 2025) employs a distillation-based algorithm to select important tokens but need to retrain the model for days, and may overfit the training data. More related works are provided in Appendix due to limited space.

C. Preliminary

Revisit of KV Caching. Modern LLMs (OpenAI, 2023; Anthropic, 2024; Touvron et al., 2023) typically perform transformer-based auto-regressive generation (Achiam et al., 2023). We begin to revisit the core self-attention (Vaswani et al., 2017) operation. For an attention layer parameterized by projection matrices $\mathbf{W}_Q, \mathbf{W}_K, \mathbf{W}_V$, the query, key, and value are computed by:

$$\mathbf{Q} = \mathbf{X}\mathbf{W}_Q, \quad \mathbf{K} = \mathbf{X}\mathbf{W}_K, \quad \mathbf{V} = \mathbf{X}\mathbf{W}_V, \tag{3}$$

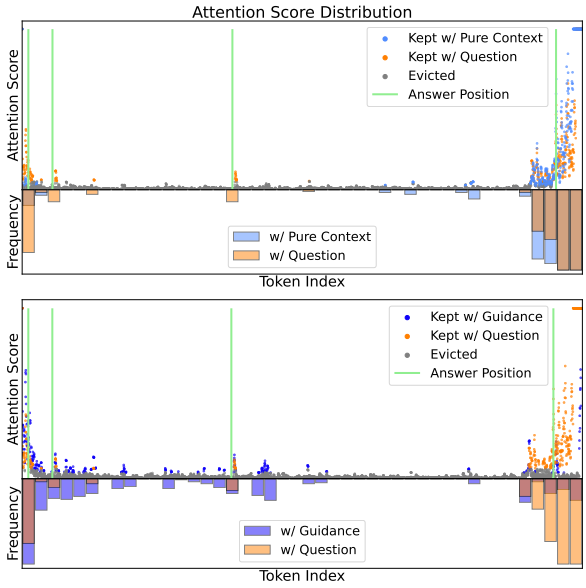

Figure 11. Visualization of attention distribution and kept KV entries (10% budget).

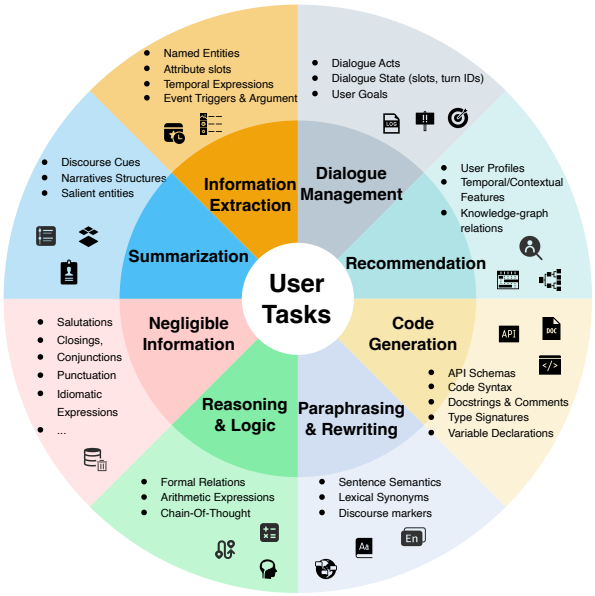

Figure 12. User preferences on task types and frequently involved information for each tasks.

with the input sequence $\mathbf{X} \in \mathrm{R}^{L \times d}$ of length L and dimension d. The self-attention is defined as (Vaswani et al., 2017):

$$\mathrm{Attention}(\mathbf{Q}, \mathbf{K}, \mathbf{V}) = \mathrm{Softmax}(\frac{\mathbf{Q}\mathbf{K}^{\mathrm{T}}}{\sqrt{d}})\mathbf{V} = \mathbf{A}\mathbf{V}, \tag{4}$$

where $\mathbf{A}$ denotes the attention matrix. During auto-regressive generation, each newly generated token $\mathbf{x}_i$ necessitates recalculating $\mathbf{Q}\mathbf{K}^{\mathrm{T}}$, which is computationally expensive. The goal of KV caching is to transform the recomputation of $\mathbf{Q}\mathbf{K}^{\mathrm{T}}$ to $\mathbf{q}_i\mathbf{K}^{\mathrm{T}}$ by caching the key and value state $\mathbf{K}$ and $\mathbf{V}$ (Pope et al., 2023):

$$\mathbf{K} = \mathrm{Concat}(\mathbf{K}, \mathbf{x}_i\mathbf{W}_K), \quad \mathbf{V} = \mathrm{Concat}(\mathbf{V}, \mathbf{x}_i\mathbf{W}_V) \tag{5}$$

where $\mathbf{q}_i = \mathbf{x}_i\mathbf{W}_Q$. Eq(5) highlights the length of KV cache grows linearly with the input sequence length, results in significant memory footprint and computational costs in long context inference.

Attention-based KV Cache Eviction. Generally, $\mathbf{X}$ is a concatenation of context $\mathbf{X}_{\text{ctx}}$ and question $\mathbf{X}_{\text{ques}}$ (or instruction). We denote its KV cache index set as Ω with sequence length $L = |\Omega|$. KV cache compression targets at exploring an subset of Ω, denoted as $\mathcal{C} = \{l_i\}_{i=1}^{B}$ and cache budget B, to maintain the model's complete capability. StreamingLLM (Xiao et al., 2024b) and LM-Infinite (Han et al., 2024) utilize a heuristic *attention sink* phenomenon to retain both initial and recent KV cache. Score based methods (Li et al., 2024a; Cai et al., 2024; Qin et al., 2025; Xiao et al., 2024a) select the top B entries based on the attention score within a L_w-long window (*i.e.* the observation window) in the tail of the context:

$$\arg\max_{\mathcal{C}} \sum_{i=L-L_w}^{L} \mathbf{A}[i, : -L_w], \quad s.t.\ |\mathcal{C}| = B. \tag{6}$$

Question-independent Scenarios. However, the success of these methods depends on identifying relevant tokens with high overlap of the observation window or indexes with high attention score. In question-independent scenario, $\mathbf{X} = \mathbf{X}_{\text{ctx}}$ and question $\mathbf{X}_{\text{ques}}$ is not given during prefilling. When the exact question $\mathbf{X}_{\text{ques}}$ is not given, these methods fail to capture crucial information related to $\mathbf{X}_{\text{ques}}$ in the context $\mathbf{X}_{\text{ctx}}$ as shown in Figure 11.

D. OracleKV

D.1. An Information Retaining Perspective of KV Cache Eviction

In this section, we investigate how an LLM can answer a question from the perspective of *retaining* information, even when only a subset of cache entries is preserved. We visualize the attention distribution induced by pure context $\mathbf{X}_{\text{ctx}}$ and the

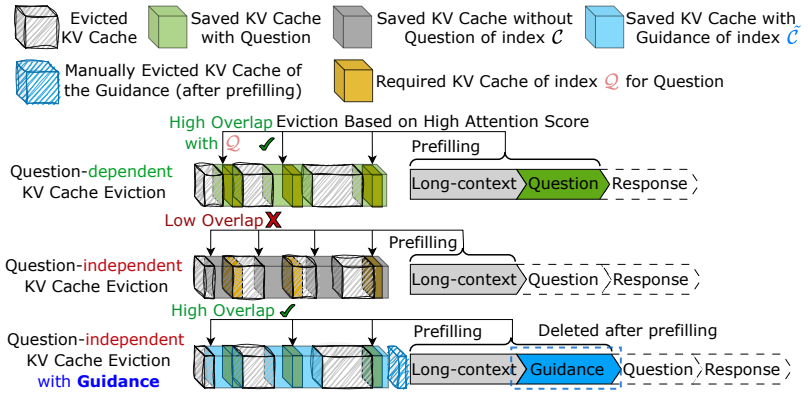

Figure 13. Overview of OracleKV. The KV entries of the context are evicted based on the attention score with oracle guidance.

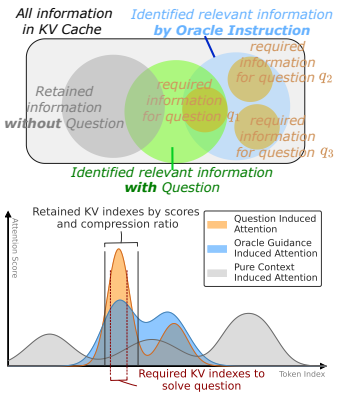

Figure 14. Attention manipulation of OracleKV.

query $\mathbf{X}_{\text{ques}}$ in Figure 11, which reveals that accuracy degradation primarily results from a mismatch between: (1) the KV cache entries retained by a given eviction algorithm, and (2) the entries actually required to answer the question, as measured by their position and relevance with the question token.

In light of this, we build a statistical model to describe the relationship between question answering and the information retaining. Formally, for an answerable question q (*i.e.* $\mathbf{X}_{\text{ques}}$), let $\mathcal{Q}$ denote the ideal set of token indexes that are critical for maintaining the model's ability to answer q. The predictive accuracy is positively correlated with $|\mathcal{Q} \cap \mathcal{C}|$, where $\mathcal{C}$ represents the set of retained cache entry indexes (defined in Sec C). The objective of KV cache compression can be summarized as to optimize the retention process so that the retained entry indexes better align with $\mathcal{Q}$, effectively ensuring that the critical information required to answer the question is preserved. We begin with the assumption of semantic types for KV entries.

Assumption D.1. Each KV entry $\mathbf{KV}_i, i \in \Omega$, its retrained information belongs to one of K semantic "types" (such as topics, concepts, etc.).

For required cache indexes $\mathcal{Q}$, the KV entries retrained information belongs to type T_i account for:

$$P_{\mathcal{Q}}(T_i) = \frac{|\{\mathbf{KV}_{\text{j}} | \text{type of } \mathbf{KV}_{\text{j}} \in T_i, j \in \mathcal{Q}\}|}{|\mathcal{Q}|}. \tag{7}$$

On the other hand, the retained cache indexes $\mathcal{C}$, under a budget $B = |\mathcal{C}|$, exhibits a type distribution given by:

$$P_{\mathcal{C}}(T_i) = \frac{|\{\mathbf{KV}_{\text{j}} | \text{type of } \mathbf{KV}_{\text{j}} \in T_i, j \in \mathcal{C}\}|}{|\mathcal{C}|}, \quad |\mathcal{C}| = B \tag{8}$$

Our goal is to show that the index overlap of retrained caches and required caches $|\mathcal{Q} \cap \mathcal{C}| \uparrow$ as the semantic type distribution $P_{\mathcal{C}}$ aligns to $P_{\mathcal{Q}}$. Based on Assumption G.1, we derive the following theorem.

Theorem D.2. *Let the semantic type of cache entries with index $\mathcal{C}$ be a discrete variable $T_{\mathcal{C}}$, and the semantic type of cache entries with index set $\mathcal{Q}$ be a discrete variable $T_{\mathcal{Q}}$. The infimum of expected predictive accuracy is positively correlated to:*

$$\inf_{\mathcal{C} \subseteq \Omega} \mathbb{E}_{T_{\mathcal{C}} \sim P_{\mathcal{C}}, T_{\mathcal{Q}} \sim P_{\mathcal{Q}}} \left(|\mathcal{Q} \cap \mathcal{C}|\right) \propto 1 - D_{\text{KL}}(P_{\mathcal{Q}} \,||\, P_{\mathcal{C}}). \tag{9}$$

Remark D.3. Theorem G.3 indicates that the infimum of predictive accuracy is inversely correlated with the KL divergence between $P_{\mathcal{Q}}$ and $P_{\mathcal{C}}$. Specifically, as $P_{\mathcal{C}}$ more closely matches $P_{\mathcal{Q}}$, the retained entries are more likely to be relevant to the query q, thereby improving predictive performance. See proofs in Appendix A.1.

D.2. Attention Manipulation via Data-level Intervention

Building on the insights from Theorem G.3, our objective is to align $P_{\mathcal{C}}(T_i)$ with $P_{\mathcal{Q}}(T_i)$ as closely as possible, ensuring that the retained entries effectively cover the semantic diversity required to answer the question. Result from Figure 11 provide a possibility to impose constraints on probability mass by manipulating attention over specific regions through data level manipulation.

Based on the idea, we aim to control the distribution of attention across semantic types in the retained entries. We resort to recent studies (Handa et al., 2025; Maslej et al., 2025) that indicates users exhibit distinct preferences across task types when interacting with large language models (LLMs). Specifically, (Handa et al., 2025) reports that over 30% of Claude (Anthropic, 2024) dialogues are dedicated to code generation tasks. In artistic fields, approximately 10% of LLM usage is devoted to writing tasks, including technical writing, advertising copy, and archival work, while report writing and book processing account for 4–6% of total dialogues. Additionally, (Handa et al., 2025) emphasizes the significance of LLMs in supporting writing refinement (*e.g.*, rewriting) and academic reading tasks (*e.g.*, information retrieval and interpretation). Moreover, (Maslej et al., 2025) underscores that the widespread adoption of LLMs hinges on their advanced capabilities in processing long-context information—such as retrieval, reasoning, and summarization—frequently applied in complex scenarios like clinical note processing. We summarize the dominant information types associated with common long-context tasks from (Handa et al., 2025; Maslej et al., 2025) in Figure 12.

We propose a data-level intervention method to manipulate attention distribution. An overview of our method is presented in Fig.13. We begin by manually designing an oracle guidance $\tilde{\mathcal{O}}$ of length L_o, which encodes surface statistics of prevalent information types in large-scale dialogues (Handa et al., 2025; Maslej et al., 2025). This oracle guidance $\tilde{\mathcal{O}}$ is then appended to the input context $\mathbf{X}_{\text{ctx}}$ as a substitude of $\mathbf{X}_{\text{ques}}$ (question q), allowing it to steer the attention distribution during the prefilling phase:

$$\mathbf{Q} = \mathbf{W}_Q \text{Concat}(\mathbf{X}_{\text{ctx}}, \tilde{\mathcal{O}}), \quad \mathbf{K} = \mathbf{W}_K \text{Concat}(\mathbf{X}_{\text{ctx}}, \tilde{\mathcal{O}}), \quad \mathbf{V} = \mathbf{W}_V \text{Concat}(\mathbf{X}_{\text{ctx}}, \tilde{\mathcal{O}}). \tag{10}$$

Following the instruction format described in (Zhou et al., 2023), we design $\tilde{\mathcal{O}}$ to encourage the model to assign higher attention to tokens representing specific information types as in Figure 14. We provide specific examples of $\tilde{\mathcal{O}}$ in Appendix. With analysis in Figure 11, we make reasonable assumption:

Assumption D.4. The attention matrix explicitly reflects the semantic correlation between KV entries.

Our goal is to select the KV entries semantically correlated to the oracle $\tilde{\mathcal{O}}$. Based on the Assumption D.4, we focus on the attention scores within the cache entry window of $\tilde{\mathcal{O}}$, as illustrated in Fig. 13, and retain the top B entries using the following criterion:

$$\arg\max_{\mathcal{C}} \sum_{i=L-L_o}^{L} \mathbf{A}[i, : -L_o], \quad \text{s.t. } |\mathcal{C}| = B. \tag{11}$$

Finally, we manually exclude the KV entries corresponding to $\tilde{\mathcal{O}}$ itself, as these surface statistics do not directly contribute to answering the query. With Theorem G.3 and Assumption D.4, Our method result in a corollary:

Corollary D.5. *Let $\tilde{\mathcal{C}}$ be the retrained index set with oracle guidance $\tilde{\mathcal{O}}$. The oracle guidance $\tilde{\mathcal{O}}$ constrains the probability mass of $P_{\tilde{\mathcal{C}}}$ over specific semantic regions R_i ($R_i \cap R_j = \emptyset,\ i \neq j$) as follows:*

$$P_{\tilde{\mathcal{C}}}(R_i) = \sum_{T_i \in R_i} P_{\mathcal{C}|\tilde{\mathcal{O}}}(T_i) = \sum_{T_i \in R_i} P_{\mathcal{Q}}(T_i) = P_{\mathcal{Q}}(R_i), \tag{12}$$

The following inequality holds:

$$\inf_{\tilde{\mathcal{C}} \subseteq \Omega} \mathbb{E}_{T_{\tilde{\mathcal{C}}} \sim P_{\tilde{\mathcal{C}}}, T_{\mathcal{Q}} \sim P_{\mathcal{Q}}} \left(|\mathcal{Q} \cap \tilde{\mathcal{C}}| \right) \geq \inf_{\mathcal{C} \subseteq \Omega} \mathbb{E}_{T_{\mathcal{C}} \sim P_{\mathcal{C}}, T_{\mathcal{Q}} \sim P_{\mathcal{Q}}} \left(|\mathcal{Q} \cap \mathcal{C}| \right) \tag{13}$$

Remark D.6. Corollary D.5 shows that oracle guidance improves predictive accuracy by redistributing probability mass over semantic types to better align with $P_{\mathcal{Q}}$, thereby enhancing the retention of relevant entries. See proofs in Appendix A.1.

E. Experiment

Datasets and Backbone LLMs. We evaluate the performance of OracleKV using several well-established benchmarks. We choose Longbench (Bai et al., 2024), RULER (Hsieh et al., 2024) and Needle-In-A-Haystack (Kamradt, 2023) to evaluate the performance of OracleKV in single-turn dialogues (matching prefix-caching scenarios), and SCBench (Li et al., 2024b) for multi-turn dialogues (matching multi-turn dialogues shared prefix-caching). Our experiments are conducted on three state-of-the-art, open-source, instruction-tuned LLMs: Mistral-7B-Instruct-v0.2, Llama-3.1-8B-Instruct, and Qwen2.5-7B-Instruct, offering context window sizes of 32K, 128K, and 1M, respectively.

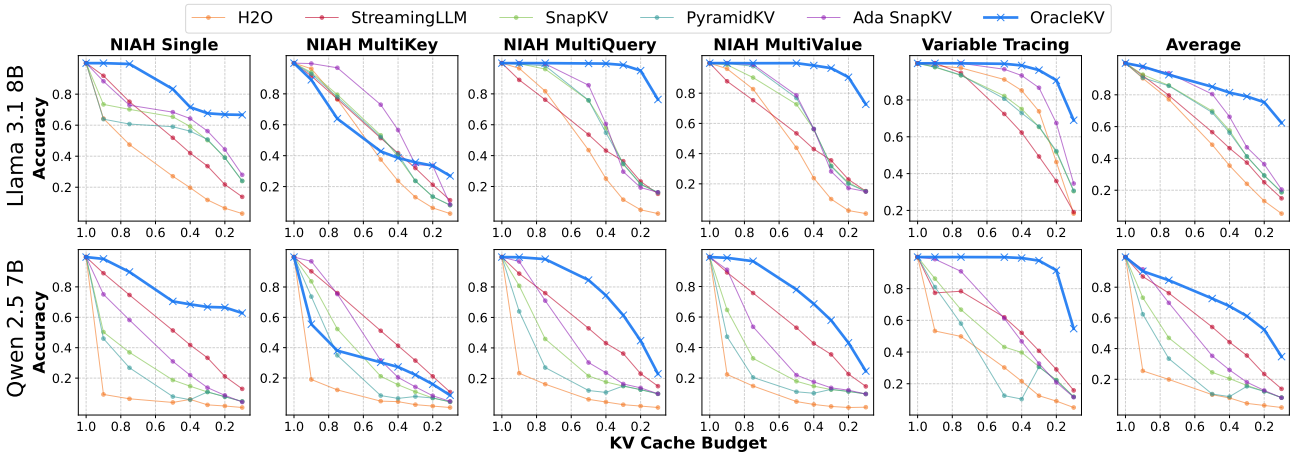

Figure 15. Performance comparison on RULER (Hsieh et al., 2024) benchmark. OracleKV provides superior KV budget and accuracy trade-off on most subtasks.

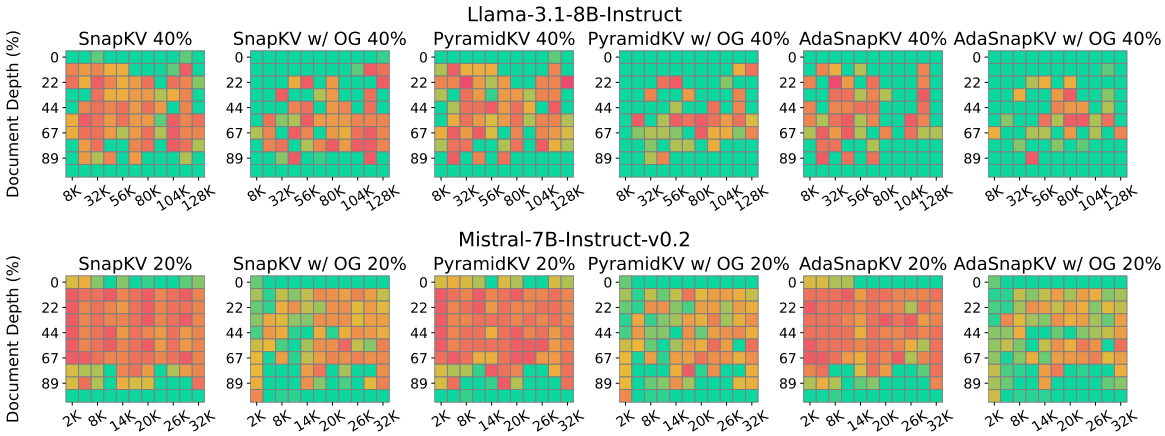

Figure 16. Oracle Guidance provides significant performance increase on the Needle-In-A-Haystack (Kamradt, 2023) pressure test while integrating into uniform (SnapKV(Li et al., 2024a)), layer-wise (PyramidKV (Cai et al., 2024)) and head-wise (Ada SnapKV (Feng et al., 2024)) budget allocation methods.

Compared Baselines. We compare OracleKV against several strong baselines categorized as: (1) *Progressive Eviction Methods*, including StreamingLLM (Xiao et al., 2024b) and H2O (Zhang et al., 2023); (2) *Selection-Based Methods*, exemplified by SnapKV (Li et al., 2024a); (3) *Layer-Level Methods*, represented by PyramidKV (Cai et al., 2024); and (4) *Head-Level Methods*, including DuoAttention (Xiao et al., 2024a) and AdaKV (Feng et al., 2024). These baselines offer a diverse range of approaches for comparison, ensuring a comprehensive evaluation of OracleKV. The detailed oracle guidance and further details regarding the implementation and justification of these baselines are provided in Appendix A.2.

E.1. Accuracy Evaluation

We evaluate OracleKV on four benchmarks: Longbench(Bai et al., 2024), RULER(Hsieh et al., 2024), Needle-In-A-Haystack(Kamradt, 2023), and SCBench (Li et al., 2024b). For Longbench and SCBench, we compare OracleKV against baselines under KV budgets of 40% and 10% with context length of 60K for Llama and 32K for Mistral. Additionally, we integrate the head-level adaptive allocation strategy from(Feng et al., 2024) into OracleKV, denoted as **Ada OracleKV**. Note that the original design of H2O (Zhang et al., 2023) is unsuitable for long-context scenarios due to its quadratic memory cost during the prefilling. We evaluate H2O on the RULER benchmark with 4K context length on both Llama and Qwen. The overall accuracy experimental results are provided in Appendix A.3.

LongBench(Bai et al., 2024) is a comprehensive multi-task benchmark suite meticulously designed to evaluate the long-context understanding capabilities of LLMs across diverse scenarios. Table 2 presents the performance of various methods

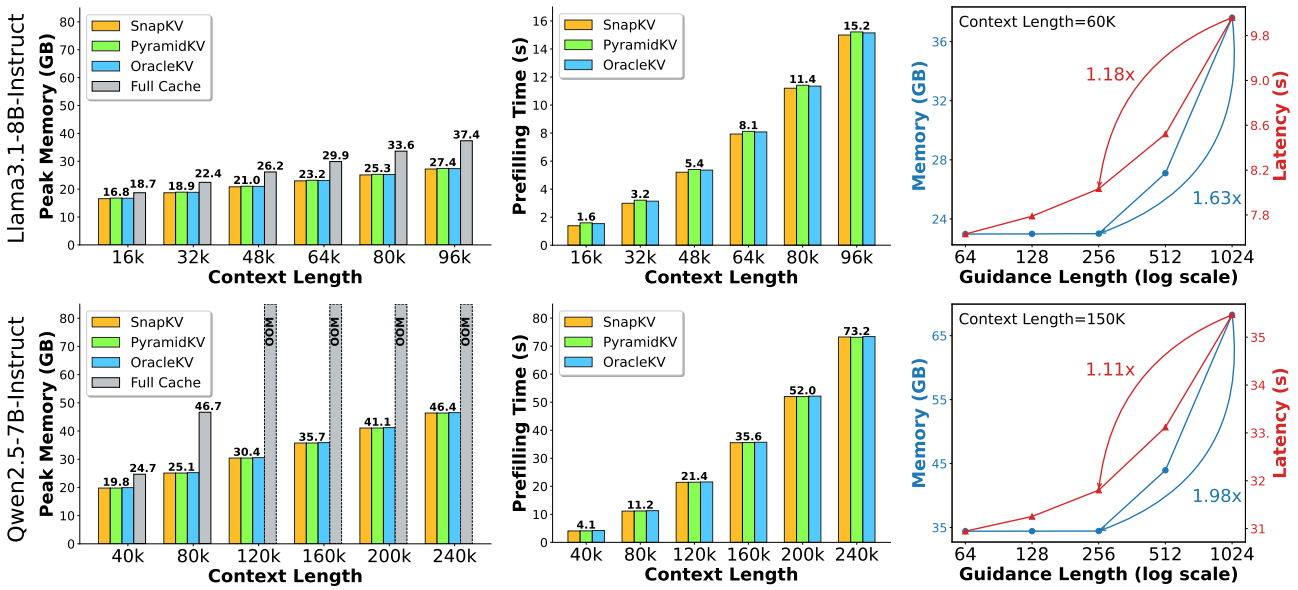

Figure 17. Prefilling latency and memory footprint of OracleKV comparing with other methods across different context length: (1) Comparison of peak memory usage. (2) Comparison of prefilling latency. (3) The computation cost scales with the length of the oracle guidance.

across five task types, encompassing 14 datasets. OracleKV consistently demonstrates superior performance on most tasks. Notably, under a 10% cache budget, OracleKV and its variant significantly outperforms other methods across solid majority of all tasks on both models, achieving an average improvement of 6.7% for Llama and 1.6% for Mistral. This result highlights its superior adaptability under extreme memory constraints.

RULER(Hsieh et al., 2024) is specifically designed benchmark to evaluate a model's ability to identify and retrieve relevant information from long contexts, which includes complex needle-in-a-haystack tests. Figure 15 illustrates the performance across five retrieval subtasks, comparing baselines with KV budgets ranging from 100% to 10%. OracleKV demonstrates an exceptional tradeoff between memory budget and accuracy across most subtasks, highlighting its strong retrieval capabilities. Notably, OracleKV experiences a minimal performance drop on three subtasks with only 30% of the KV budget.

Needle-In-A-Haystack (NIAH)(Kamradt, 2023) is a widely adopted benchmark designed to rigorously assess a model's ability to retrieve a specific string (the "needle") from a context (the "haystack"). As shown in Figure16, baseline methods struggle to extract the correct answer from contexts of varying depths. Notably, these methods demonstrate significant improvement when integrated with Oracle Guidance, highlighting its effectiveness in refining retrieval accuracy. This performance boost is particularly evident in deeper contexts, where other methods typically experience sharp declines in retrieval precision. OracleKV's robust handling of long-context scenarios thus proves crucial in improving the model's overall reliability in practical retrieval tasks.

Multi-turn Benchmark. To investigate performance in real-world multi-turn dialogues, we evaluate OracleKV along with all baselines on the multi-turn SCBench(Li et al., 2024b). SCBench is a challenging KV-centric multi-turn benchmark that includes various tasks such as QA, choice, summary, and many-shot in-context learning, where each shared context involves at least four turns of dialogue. Table2 shows that OracleKV consistently outperforms all other baselines on most tasks, maintaining superior performance under the same KV budget across all three models.

E.2. Efficiency Evaluation

We evaluate the prefilling latency and memory footprint of Oralce on Llama-3.1-8B-Instruct for 96K context prefilling and Qwen2.5-7B-Instruct for 240K context prefilling. All experiments are conducted with a fixed 4K KV cache budget BF16 inference on a single A100 GPU. Since the primary goal of OracleKV is to compress KV cache in context-only scenarios without on-the-fly requirement, we do not evaluate its decoding efficiency.

Peak Memory Usage. As shown in 17(1), OracleKV shows comparable memory savings with uniform budget allocation strategies (SnapKV (Li et al., 2024a)) and layer-pattern budget allocation strategies (PyramidKV (Cai et al., 2024)), both of which significantly reduce memory consumption compared to full attention. Notably, OracleKV saves 26.7% with on Llama

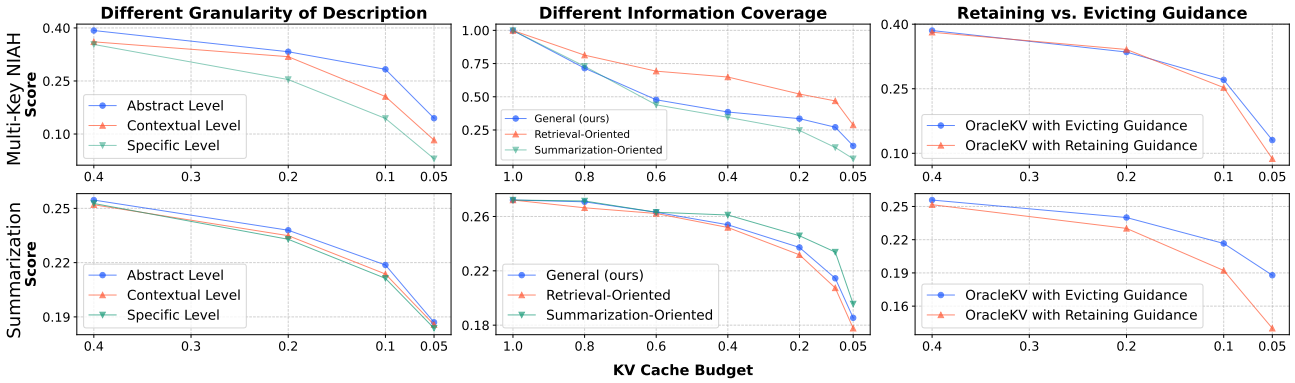

Figure 18. Ablation studies of OracleKV: (1) Comparison of OracleKV with varying descriptive granularity, showing the superior of high-level descriptive oracle guidance. (2) Analysis of OracleKV with guidance with different information coverage, showing the task-specific guidance results in performance increase on corresponding task but with the loss of generalization capability accordingly. (3). Comparison of retraining and evicting the KV entries of oracle guidance.

model with 96K context length, while saving more than 62% memory on Qwen model with 120K context length.

Prefilling Latency (Time-To-First-Token). Figure 17(2) illustrates the prefilling latency for each method. OracleKV achieves comparable prefilling speed to PyramidKV (fixed-pattern allocation) while being marginally slower than SnapKV (uniform allocation). This tradeoff reflects the efficient cache management of OracleKV.

Computational Cost with Guidance Length. To further investigate the computational efficiency of OracleKV, we examine how its memory footprint and prefilling latency scale with the guidance length, using context lengths of 64K and 150K. As shown in Figure 17(3), the memory usage increases significantly beyond a guidance length of 512 tokens. For a guidance length of 1K, peak memory usage increases by 1.63× and 1.98× for 64K and 150K contexts, respectively. Prefilling latency (TTFT) also increases, with a 1.18× increase for the 64K context and a 1.11× increase for the 150K context. These findings illustrate the tradeoffs between guidance length and computational efficiency in OracleKV, providing insights into optimal configuration choices for various scenarios.

E.3. Ablation Study

We perform ablation studies on the multi-key retrieval and summarization tasks to investigate the effect of various design choices in OracleKV, with Llama-3.1-8B-Instruct model of KV cache budget ranging from full cache to 5% budget. Appendix A.4 presents more specific design of OracleKV.

Descriptive Granularity. We examine the effect of descriptive granularity in oracle guidance with three levels: (1)*Abstract Level*: the oracle guidance provides generalized instructions, such as "Please remember the specific details." (2) *Contextual Level*: The guidance specifies information types as "Please remember the numerical information." (3) *Specific Level*: The guidance explicitly lists information types with examples, such as "Please remember numerical information, such as timelines, birthdays, and percentages." As shown in Figure 18(1), contrary to our initial expectations, the abstract-level guidance outperforms other two on both tasks, suggesting that concise, high-level instructions are more effective in guiding the model than overly detailed descriptions.

Information Coverage of Oracle Guidance. We further explore the impact of information coverage in oracle guidance by tailoring the guidance to the target task (e.g., specifying "This is a retrieval task."). Figure 18(2) shows that task-specific guidance significantly enhances performance on the corresponding task but leads to performance degradation on other tasks. In contrast, the default general (surface-level) guidance achieves balanced performance across all tasks. This finding indicates that task-specific oracle guidance can significantly boost performance when the task is explicitly known. However, it also impair the model's generalization capabilities, accordingly.

Retraining vs. Evicting Oracle Guidance. Finally, we investigate the effect of maintaining or evicting oracle guidance in the KV cache. As shown in Figure 18(3), retaining oracle guidance leads to a substantial performance drop as the KV cache budget decreases. This decline occurs because the oracle guidance–descriptive rather than factual–occupies valuable KV cache space without contributing directly to the task's answer. evicting the oracle guidance effectively mitigating the adverse impact of retaining invasive, non-essential guidance.

F. Conclusion

We present OracleKV, a data-level intervention approach designed for question-independent KV cache compression. OracleKV steers the attention distribution of by appending an oracle guidance to the pure context. It then selects KV entries that are semantically correlated with oracle guidance based on attention score. Comprehensive experiments demonstrate OracleKV results in a significant performance increase on four long-context benchmarks under question-independent setting. We do not claim that OracleKV alone constitutes a state-of-art data-level solution for KV cache compression. Rather, we view it as a promising step toward more adaptive and context-aware cache compression. With extensive validation and development, OracleKV could serve as an useful component within a broader, more comprehensive framework for long-context inference.

Table 2. Average performance of various baselines across different LLMs in single-turn (Bai et al., 2024) and multi-turn (Li et al., 2024b) benchmarks. We compare OracleKV with baselines under 40% and 10% KV budget.

Method	Budget	Single-turn LongBench						Multi-turn SCBench						
		Sin.QA	Mul.QA	Sum.	Few.Shot.	Syn.	AVG.	M.C.	M.S.	M.F.	QA.En	QA.Ch	Sum.	AVG.
LLaMA-3.1-8B-Instruct														
Full Cache	100%	44.3	47.0	29.2	51.1	55.6	45.7	5.7	40.0	28.0	20.9	27.5	30.9	25.8
StreamingLLM	40%	27.9	34.6	25.7	53.4	26.1	33.5	7.9	38.2	12.2	18.0	16.3	22.3	19.1
SnapKV	40%	35.3	44.8	26.5	53.6	54.5	42.9	6.1	44.4	22.5	17.8	23.5	27.7	23.7
PyramidKV	40%	34.1	35.3	25.7	55.3	51.5	40.4	5.5	42.8	19.5	18.6	19.9	23.5	21.6
Ada SnapKV	40%	37.0	45.6	26.7	55.1	54.3	44.1	5.7	40.4	19.8	19.3	24.0	28.3	22.9
DuoAttention	40%	42.4	44.3	27.2	53.5	52.8	43.5	8.3	39.6	15.3	18.6	25.4	29.4	22.8
OracleKV	40%	40.9	46.4	27.4	54.0	56.1	45.0	5.2	44.2	23.3	20.5	25.7	29.8	24.8
Ada OracleKV	40%	42.0	45.5	27.6	53.4	55.8	44.9	5.7	43.0	22.9	20.5	27.2	30.5	24.9
StreamingLLM	10%	20.7	24.6	21.3	51.0	10.0	25.5	6.6	38.9	12.0	15.6	10.1	20.8	17.3
SnapKV	10%	22.6	29.6	21.7	51.6	29.5	30.1	6.1	50.7	21.2	15.2	14.5	22.3	21.7
PyramidKV	10%	21.3	24.0	21.7	51.8	27.1	29.2	5.2	48.8	20.6	13.6	11.0	21.4	20.1
Ada SnapKV	10%	24.1	30.7	22.3	51.7	31.5	32.1	5.7	50.4	20.3	14.7	15.9	23.0	21.7
DuoAttention	10%	18.2	23.3	21.4	49.4	28.0	28.1	7.4	47.4	19.7	12.3	7.6	25.3	20.0
OracleKV	10%	24.5	33.2	23.5	56.3	45.3	36.5	6.1	45.2	21.3	18.5	18.1	25.9	22.5
Ada OracleKV	10%	28.8	34.0	23.8	58.3	49.3	38.8	5.7	50.4	21.0	17.0	19.3	26.3	23.3
Mistral-7B-Instruct-v0.2														
Full Cache	100%	32.1	24.3	27.7	55.4	38.5	35.6	11.4	64.1	5.7	6.1	10.1	24.0	20.2
StreamingLLM	40%	19.5	18.5	25.4	46.3	16.6	25.3	11.4	57.0	6.0	6.0	8.0	19.3	18.0
SnapKV	40%	23.9	19.4	25.2	53.9	37.9	32.0	10.5	59.3	3.7	6.8	9.1	23.1	18.7
PyramidKV	40%	23.9	20.8	25.1	54.7	34.0	31.7	11.4	61.1	5.7	6.7	9.5	22.5	19.5
Ada SnapKV	40%	24.3	20.0	24.5	53.5	35.6	31.6	11.1	58.5	5.5	6.7	9.7	23.8	19.2
DuoAttention	40%	15.3	14.4	22.4	44.0	6.3	20.5	9.6	56.3	3.5	5.9	4.6	23.7	17.3
OracleKV	40%	25.4	21.1	26.3	53.6	37.2	32.7	11.9	62.6	5.7	6.4	9.5	23.9	20.0
Ada OracleKV	40%	26.4	21.3	26.2	53.7	37.8	33.1	11.5	61.5	4.5	6.4	10.3	24.3	19.7
StreamingLLM	10%	13.9	12.5	21.3	38.6	6.9	18.7	10.5	61.1	3.0	4.5	5.0	20.0	17.4
SnapKV	10%	15.1	13.5	21.8	49.5	23.0	24.6	9.6	59.4	3.2	5.7	6.2	20.5	17.4
PyramidKV	10%	14.6	13.7	21.6	49.2	21.6	24.1	8.3	60.2	6.8	5.2	6.5	20.3	17.9
Ada SnapKV	10%	15.9	14.4	21.7	50.3	26.6	25.8	9.7	59.1	4.6	5.7	6.7	21.1	17.8
DuoAttention	10%	14.0	13.1	20.4	40.8	5.3	18.7	9.2	48.9	2.2	4.4	3.6	21.0	14.9
OracleKV	10%	17.6	13.7	23.3	49.1	26.9	26.1	10.5	59.9	6.0	5.5	8.8	21.1	18.6
Ada OracleKV	10%	18.3	14.1	23.5	48.3	32.6	27.4	10.9	59.7	4.3	5.7	9.1	21.9	18.6

Limitation and Broader Impact

Limitation. While OracleKV has been experimentally demonstrated to introduce useful inductive bias for KV cache eviction, it is not exempt from the ”no free lunch” theorem–oracle guidance inevitably entails certain side effects. Specifically, we observe that in some specialized tasks, such as code generation, where issues related to token frequency are prominent, the general oracle guidance employed by OracleKV may fail to yield significant improvements. In some cases, it may even degrade the performance of the LLM on these tasks. Though, designing task-specific oracle guidance can enhance performance in such scenarios. However, as highlighted in our ablation study, this approach still suffers from side effects in other tasks.

Moreover, OracleKV involves the computation and explicitly return of the windowed attention matrix, which, to the best of our knowledge, cannot be optimized using memory-efficient techniques like flash attention (Dao et al., 2022; Dao, 2024). This limitation not only leads to notable latency but also results in high memory usage. In environments with rigorous memory peak requirements, such as edge devices, this necessitates carefully design within the length limit of oracle guidance for KV cache eviction. Nevertheless, as demonstrated in our ablation experiments, longer and more detailed oracle guidance does not always correlate with better performance.

Broader Impact. OracleKV provides a new perspective to guide KV cache eviction in large language models (LLMs) by leveraging data-level intervention to introduce inductive biases. While OracleKV demonstrates significant performance improvements in question-independent eviction settings, its potential extension to other setting (such as question-aware or task-oriented KV cache eviction) presents a exciting direction for future research. Additionally, the limitations of OracleKV, especially the task-specific nature of its benefits and the increased computational and memory overhead, highlight important trade-offs in the practical deployment. In particular, the increased latency and memory consumption could pose challenges for real-time applications on resource-constrained devices. Furthermore, the need for task-specific oracle design raises concerns about scalability and generalizability, potentially reinforcing disparities between well-resourced and low-resource tasks or domains. We believe that future work should explore more efficient and generalizable oracle guidance designs that balance interpretability, performance, and system efficiency, ensuring that such techniques can be equitably applied across a broad range of use cases.

G. Supplementary Results

G.1. Complete Assumptions/Proofs for Theoretical Results

Assumption G.1. type Each KV entry $\mathbf{KV}_i, i \in \Omega$, its retrained information belongs to one of K semantic "types" (such as topics, concepts, etc.).

For required cache indexes $\mathcal{Q}$, the KV entries retrained information belongs to type T_i account for:

$$P_{\mathcal{Q}}(T_i) = \frac{|\{\mathbf{KV}_\mathrm{j} | \mathrm{type}(\mathbf{KV}_\mathrm{j}) \in T_i, j \in \mathcal{Q}\}|}{|\mathcal{Q}|}. \tag{14}$$

On the other hand, the retained cache indexes $\mathcal{C}$, under a budget $B = |\mathcal{C}|$, exhibits a type distribution given by:

$$P_{\mathcal{C}}(T_i) = \frac{|\{\mathbf{KV}_\mathrm{j} | \mathrm{type}(\mathbf{KV}_\mathrm{j}) \in T_i, j \in \mathcal{C}\}|}{|\mathcal{C}|}, \quad |\mathcal{C}| = B \tag{15}$$

Our goal is to show that the index overlap of retrained caches and required caches $|\mathcal{Q} \cap \mathcal{C}| \uparrow$ as the semantic type distribution $P_{\mathcal{C}}$ aligns to $P_{\mathcal{Q}}$. Based on Assumption G.1, we derive the following theorem.

Lemma G.2. (Pinsker's inequality) Let P and Q be two distributions defined on a universe U, then

$$D_{\mathrm{KL}}(P \mid\mid Q) \geq \frac{1}{2}||P - Q||_1^2 \tag{16}$$

We first prove the above inequality for the special case of $U = \{0, 1\}$. Then we show how one can prove the general case, by reducing it to the binary case.

Proof of Lemma G.2. For the binary case:

$$P = \begin{cases} 1, & \text{w.p. } p \\ 0, & \text{w.p. } 1-p \end{cases} \qquad Q = \begin{cases} 1, & \text{w.p. } q \\ 0, & \text{w.p. } 1-q \end{cases} \tag{17}$$

We assume $p \geq q$ (proof of $q \geq p$ is similar), and let

$$f(p, q) = p \log \frac{p}{q} + (1-p) \log \frac{1-p}{1-q} - \frac{1}{2 \ln 2}(2(p-q))^2. \tag{18}$$

Since

$$\frac{\partial f}{\partial q} = -\frac{p-q}{\ln 2}\left(\frac{1}{q(1-q)} - 4\right) \leq 0, \tag{19}$$

and $f = 0$ when $q = p$, we conclude that $f(p, q) \geq 0$ where $q \leq p$. By change the logarithm base from 2 to e, we have $D_{\mathrm{KL}}(P \mid\mid Q) \geq \frac{1}{2}||P - Q||_1^2$ for this special case. We consider the general case. Let P and Q be distributions on U, let $A \subset U$ be

$$A = \{x \mid p(x) \geq q(x)\}. \tag{20}$$

And P_A, Q_A be

$$P_A := \begin{cases} 1, & \text{w.p. } \sum_{x \in A} p(x) \\ 0, & \text{w.p. } \sum_{x \notin A} p(x) \end{cases} \qquad Q_A := \begin{cases} 1, & \text{w.p. } \sum_{x \in A} q(x) \\ 0, & \text{w.p. } \sum_{x \notin A} q(x) \end{cases} \tag{21}$$

Then,

$$\begin{aligned} ||P - Q||_1 &= \sum_x |p(x) - q(x)| && (22) \\ &= \sum_{x \in A}(p(x) - q(x)) + \sum_{x \notin A}(q(x) - p(x)) && (23) \\ &= \left|\sum_{x \in A} p(x) - \sum_{x \in A} q(x)\right| + \left|\left(1 - \sum_{x \notin A} p(x)\right) + \left(1 - \sum_{x \notin A} q(x)\right)\right| && (24) \\ &= ||P_A - Q_A||_1 && (25) \end{aligned}$$

To caculate the KL-divergence, we define the random variable

$$Z = \begin{cases} 1, & \text{if } x \in A, \\ 0, & \text{if } x \notin A. \end{cases} \tag{26}$$

Since Z is a function of X, we can also think of the two distributions P and Q as joint distributions for the random variables (X, Z). Applying the chain rule for KL-divergence gives

$$\begin{aligned} D_{\mathrm{KL}}(P \,||\, Q) &= D_{\mathrm{KL}}(P(X,Z) \,||\, Q(X,Z)) && (27)\\ &= D_{\mathrm{KL}}(P(Z) \,||\, Q(Z)) + D_{\mathrm{KL}}(P(X|Z) \,||\, Q(X|Z)) && (28)\\ &\geq D_{\mathrm{KL}}(P(Z) \,||\, Q(Z)) && (29)\\ &= D_{\mathrm{KL}}(P_A \,||\, Q_A) && (30)\\ &\geq \frac{1}{2}||P_A - Q_A||^2 && (31)\\ &= \frac{1}{2}||P - Q||_1^2, && (32) \end{aligned}$$

which completes the proof.

Theorem G.3. (Theorem 4.2) Let the semantic type of cache entries with index $\mathcal{C}$ be a discrete variable $T_{\mathcal{C}}$, and the semantic type of cache entries with index set $\mathcal{Q}$ be a discrete variable $T_{\mathcal{Q}}$. The lowerbound of expected predictive accuracy is positively correlated to:

$$\inf_{\mathcal{C} \subseteq \Omega} \mathbb{E}_{T_{\mathcal{C}} \sim P_{\mathcal{C}}, T_{\mathcal{Q}} \sim P_{\mathcal{Q}}} \left(|\mathcal{Q} \cap \mathcal{C}|\right) \propto 1 - D_{\mathrm{KL}}(P_{\mathcal{Q}} \,||\, P_{\mathcal{C}}). \tag{33}$$

Proof. Let $N_i = \{\mathrm{KV_j} \mid \mathrm{type}(\mathrm{KV_j}) \in T_i, j \in \Omega\}$ For a questions with required information type T_i, for a long-context, the model is possible to answer it correctly only when the retained KV caches contain the information of type T_i. *i.e.*

$$\begin{aligned} \mathbb{E}\left(|\mathcal{Q} \cap \mathcal{C}|\right) &\propto \sum_i \frac{|\mathcal{Q}| P_{\mathcal{Q}}(T_i) \cdot B P_{\mathcal{C}}(T_i)}{N_i} = |\mathcal{Q}| \cdot B \sum_i \frac{P_{\mathcal{Q}}(T_i) P_{\mathcal{C}}(T_i)}{N_i}, && (34)\\ &\propto \sum_{t \in \Omega^{\mathcal{T}}} P_{\mathcal{Q}}(t) P_{\mathcal{C}}(t) = \langle P_{\mathcal{Q}}, P_{\mathcal{C}} \rangle. && (35) \end{aligned}$$

Where $\Omega^{\mathcal{T}}$ is the type space. Consider

$$\langle P_{\mathcal{Q}}, P_{\mathcal{C}} \rangle = 1 - \frac{1}{2} \sum_{t \in \Omega^{\mathcal{T}}} (P_{\mathcal{Q}}(t) - P_{\mathcal{C}}(t))^2 = 1 - \frac{1}{2}||P_{\mathcal{Q}} - P_{\mathcal{C}}||_2^2, \tag{36}$$

since $||x||_2 \leq ||x||_1$, we have

$$||P_{\mathcal{Q}} - P_{\mathcal{C}}||_2^2 \leq ||P_{\mathcal{Q}} - P_{\mathcal{C}}||_1^2. \tag{37}$$

By Pinsker's inequality (Lemma G.2), we have

$$||P_{\mathcal{Q}} - P_{\mathcal{C}}||_1 \leq \sqrt{2 D_{\mathrm{KL}}(P_{\mathcal{Q}} \,||\, P_{\mathcal{C}})}, \tag{38}$$

then substitute Eq(38) to Eq(35) and we have

$$\mathbb{E}\left(|\mathcal{Q} \cap \mathcal{C}|\right) \propto \sum_{t \in \Omega^{\mathcal{T}}} P_{\mathcal{Q}}(t) P_{\mathcal{C}}(t) \geq 1 - D_{\mathrm{KL}}(P_{\mathcal{Q}} \,||\, P_{\mathcal{C}}), \tag{39}$$

which completes the proof.

Corollary G.4. *Let $\tilde{\mathcal{C}}$ be the retrained index set with oracle guidance $\tilde{\mathcal{O}}$. The oracle guidance $\tilde{\mathcal{O}}$ constrains the probability mass of $P_{\tilde{\mathcal{C}}}$ over specific semantic regions R_i $(R_i \cap R_j = \emptyset,\ i \neq j)$ as follows:*

$$P_{\tilde{\mathcal{C}}}(R_i) = \sum_{T_i \in R_i} P_{\mathcal{C}|\tilde{\mathcal{O}}}(T_i) = \sum_{T_i \in R_i} P_{\mathcal{Q}}(T_i) = P_{\mathcal{Q}}(R_i), \tag{40}$$

The following inequality holds:

$$\inf_{\tilde{\mathcal{C}} \subseteq \Omega} \mathbb{E}_{T_{\tilde{\mathcal{C}}} \sim P_{\tilde{\mathcal{C}}}, T_{\mathcal{Q}} \sim P_{\mathcal{Q}}} \left(|\mathcal{Q} \cap \tilde{\mathcal{C}}|\right) \geq \inf_{\mathcal{C} \subseteq \Omega} \mathbb{E}_{T_{\mathcal{C}} \sim P_{\mathcal{C}}, T_{\mathcal{Q}} \sim P_{\mathcal{Q}}} \left(|\mathcal{Q} \cap \mathcal{C}|\right) \tag{41}$$

Proof of Corollary G.4. Based on Theorem G.3, we show above inequality by proving $D_{\mathrm{KL}}(P_{\mathcal{Q}} \,||\, P_{\tilde{\mathcal{C}}}) \leq D_{\mathrm{KL}}(P_{\mathcal{Q}} \,||\, P_{\mathcal{C}})$. We first define a random variable Z that indicates the region to which a type T belongs to $Z = i$ if $T \in R_i$. Since the regions are disjoint and exhaustive, Z is a deterministic function of T, The chain rule for KL-divergence allows us to express the divergence over the joint distribution of (T, Z):

$$D_{\mathrm{KL}}(P(T) \,||\, Q(T)) = D_{\mathrm{KL}}(P(Z) \,||\, Q(Z)) + \sum_z D_{\mathrm{KL}}(P(T|Z=z) \,||\, Q(T|Z=z)), \tag{42}$$

where $P(Z)$ and $Q(Z)$ are the marginal distributions over the regions, and $P(T|Z=z)$ and $Q(T|Z=z)$ are the conditional distributions within region z. KL-divergence calculation:

$$D_{\mathrm{KL}}(P_{\mathcal{Q}} \,||\, P_{\mathcal{C}}) = D_{\mathrm{KL}}(P_{\mathcal{Q}}(Z) \,||\, P_{\mathcal{C}}(Z)) + \sum_i P_{\mathcal{Q}}(Z=i) D_{\mathrm{KL}}(P_{\mathcal{Q}}(T|Z=i) \,||\, P_{\mathcal{C}}(T|Z=i)) \tag{43}$$

where

$$P_{\mathcal{Q}}(Z=i) = P_{\mathcal{Q}}(R_i) = \sum_{t \in R_i} P_{\mathcal{Q}}(t) \tag{44}$$

$$P_{\mathcal{C}}(Z=i) = P_{\mathcal{C}}(R_i) = \sum_{t \in R_i} P_{\mathcal{C}}(t) \tag{45}$$

$$P_{\mathcal{Q}}(T=t|Z=i) = \frac{P_{\mathcal{Q}}(t)}{P_{\mathcal{Q}}(R_i)}, \text{ w.r.t. } t \in R \tag{46}$$

$$P_{\mathcal{C}}(T=t|Z=i) = \frac{P_{\mathcal{C}}(t)}{P_{\mathcal{C}}(R_i)}, \text{ w.r.t. } t \in R \tag{47}$$

And then we calculate

$$D_{\mathrm{KL}}(P_{\mathcal{Q}} \,||\, P_{\tilde{\mathcal{C}}}) = D_{\mathrm{KL}}(P_{\mathcal{Q}}(Z) \,||\, P_{\tilde{\mathcal{C}}}(Z)) + \sum_i P_{\mathcal{Q}}(Z=i) D_{\mathrm{KL}}(P_{\mathcal{Q}}(T|Z=i) \,||\, P_{\tilde{\mathcal{C}}}(T|Z=i)) \tag{48}$$

Assumption G.5. The type distribution $P_{\mathcal{C}}$ and $P_{\tilde{\mathcal{C}}}$ are identical on regions R_i in the sense of expectation. or

$$D_{\mathrm{KL}}[P_{\mathcal{Q}}(T|Z=i) \,||\, P_{\tilde{\mathcal{C}}}(T|Z=i)] = D_{\mathrm{KL}}[P_{\mathcal{Q}}(T|Z=i) \,||\, P_{\mathcal{C}}(T|Z=i)] \tag{49}$$

Then we compare the KL-divergence

$$D_{\mathrm{KL}}(P_{\mathcal{Q}} \,||\, P_{\mathcal{C}}) - D_{\mathrm{KL}}(P_{\mathcal{Q}} \,||\, P_{\tilde{\mathcal{C}}}) \tag{50}$$

$$= [D_{\mathrm{KL}}(P_{\mathcal{Q}}(Z) \,||\, P_{\mathcal{C}}(Z)) - D_{\mathrm{KL}}(P_{\mathcal{Q}}(Z) \,||\, P_{\tilde{\mathcal{C}}}(Z))] \tag{51}$$

$$+ [\sum_i P_{\mathcal{Q}}(Z=i) D_{\mathrm{KL}}(P_{\mathcal{Q}}(T|Z=i) \,||\, P_{\mathcal{C}}(T|Z=i)) \tag{52}$$

$$- \sum_i P_{\mathcal{Q}}(Z=i) D_{\mathrm{KL}}(P_{\mathcal{Q}}(T|Z=i) \,||\, P_{\tilde{\mathcal{C}}}(T|Z=i))] \tag{53}$$

By Assumption G.5, the second term vanishes. For the first term, since

$$D_{\mathrm{KL}}(P_{\mathcal{Q}}(Z) \,||\, P_{\tilde{\mathcal{C}}}(Z)) = \sum_i P_{\mathcal{Q}}(Z=i) \ln \frac{P_{\mathcal{Q}}(R_i)}{P_{\tilde{\mathcal{C}}}(R_i)} \tag{54}$$

$$= \sum_i P_{\mathcal{Q}}(R_i) \ln \frac{P_{\mathcal{Q}}(R_i)}{P_{\mathcal{Q}}(R_i)} = 0, \tag{55}$$

thus we have

$$D_{\mathrm{KL}}(P_{\mathcal{Q}} \,||\, P_{\mathcal{C}}) - D_{\mathrm{KL}}(P_{\mathcal{Q}} \,||\, P_{\tilde{\mathcal{C}}}) = D_{\mathrm{KL}}(P_{\mathcal{Q}}(Z) \,||\, P_{\mathcal{C}}(Z)) \geq 0, \tag{56}$$

which completes the proof.

G.2. Implementation Details

Table A3. Detailed dataset configuration of all experiments. Our experiments involve four datasets with comprehensive datasets and varying context length.

Benchmark	Task	Dataset	Average Length	Test Length
LongBench (Bai et al., 2024)	Single-Document QA	NartvQA Qasper MultiFieldQA-En	18409 3619 6701	60000(Llama) 32000(Mistral)
	Multi-Document QA	HotpotQA 2WikiMQA Musique	9151 4887 11214	
	Summarization	GovReport QMSum MultiNews	8734 10614 2113	
	Few-shot Learning	TREC TriviaQA SAMSum	5177 8209 6258	
	Synthetic	Passage Count Passage Retrieval	11141 9289	
	Code	Lcc Repobench-p	1235 4206	
SCBench (Li et al., 2024b)	Multiple Choice	Multiple Choice	188000	
	In-Context Learning	Many Shot	22000	
	Math Find	Math Find	120000	
	Question Answering	QA.En QA.Ch	198000 1500000	
	Summarization	Summarization	18409	
RULER (Hsieh et al., 2024)	NIAH Single	NIAH-Single-1 NIAH-Single-2 NIAH-Single-3	4000	4000 for Llama and Qwen
	NIAH Multikey	NIAH-Multikey-1 NIAH-Multikey-2 NIAH-Multikey-3		
	NIAH-Multiquery	Summarization		
	NIAH-Multivalue	Summarization		
	Variable Tracing	Variable Tracing		
	Word Extraction	Common Word Extraction Frequent Word Extraction		
	Question Answering	QA.1 QA.2		
Needle-In- -A-Haystack (Kamradt, 2023)	NIAH Single	Synthetic	depth 0%∼100%	2K∼32K(Mistral) 8K∼128K(Llama)

G.2.1. Dataset Configuration

We adopt four benchmark datasets for our experiments: LongBench(Bai et al., 2024), RULER(Hsieh et al., 2024), and Needle-In-A-Haystack(Kamradt, 2023). Detailed configurations of the datasets used are provided in TableA3.

For LongBench, we evaluate OracleKV and compare it with baseline methods on 14 tasks (excluding code-related tasks).

Results for the code tasks are reported separately in the subsequent section. Due to the unavailability of head-level identification files for Qwen2.5(Yang et al., 2024a), we omit the DuoAttention(Xiao et al., 2024a) results on Qwen2.5.

Regarding H2O (Zhang et al., 2023), its original design is not well-suited for long-context inference (e.g., 32K tokens) due to the high memory cost of window attention, which leads to out-of-memory (OOM) errors for context lengths exceeding 11K tokens.

For RULER, we use a 4K context length to evaluate and compare the performance of OracleKV and other baselines on a subset of the tasks.

G.2.2. Examples of Oracle Guidance

Table A4 provides some examples of the oracle guidance. The general oracle guidance contain that we use for accuracy and efficiency experiments. The task-specific oracle guidance contain that we we use for ablation experiments.

G.2.3. Details of Experimental Environment and Baseline

We use PyTorch 2.3.1 as our primary experimental platform. Our implementation is based on the NVIDIA KVPress repository (kvp, 2025), which also serves as the codebase for most baseline methods.

All experiments are conducted using a server equipped with an AMD EPYC 7742 64-Core Processor, 256 GB of CPU memory, and four GPUs: three NVIDIA L40 GPUs for accuracy evaluations and ablation studies, and one NVIDIA A100 GPU for efficiency experiments.

For H2O(Zhang et al., 2023), since the original algorithm is not designed to perform KV cache eviction during the prefilling stage, we modify it to begin eviction only after prefilling is complete. For DuoAttention(Xiao et al., 2024a), whose effective compression ratio varies dynamically with input length, we adaptively set the head compression ratio per input to maintain a fixed KV cache budget. Additionally, to ensure a fair comparison, we disable all on-the-fly decoding mechanisms across all baselines.

G.3. Supplementary Accuracy Evaluation Results

G.3.1. Supplementary Results for LongBench

We present the detailed results on LongBench (Bai et al., 2024) in Table A5, Table A6, and Table A7. These include extended evaluations of Qwen2.5-7B-Instruct-1M on LongBench, as well as two additional code datasets that are not reported in the main paper.

We observe that LLaMA-3.1-8B-Instruct is generally more robust than both Mistral-7B-Instruct-v0.2 and Qwen2.5-7B-Instruct-1M across tasks. Notably, the performance of KV cache compression methods on multi-document QA datasets—such as HotpotQA and MuSiQue (Table A5)—tends to be unstable. In some cases, the compressed models actually outperform the full model. This is especially pronounced with Qwen2.5-7B-Instruct-1M, where several KV compression methods exceed the full-model performance on both single-document QA (e.g., NarrativeQA) and multi-document QA (e.g., MuSiQue).

Interestingly, OracleKV leads to slight degradation on some multi-document QA datasets (e.g., 2WikiMQA) compared to head-level compression methods such as DuoAttention(Xiao et al., 2024a) and Ada SnapKV(Feng et al., 2024), under the 40% KV cache budget. However, under the extreme condition of a 10% KV cache budget, OracleKV consistently outperforms all other methods across nearly all single- and multi-document QA datasets, highlighting its strong adaptability in low-memory scenarios.

As shown in Table A6, most KV cache compression methods lead to performance improvements on few-shot learning and in-context learning tasks across all three models—particularly on the TREC dataset. This suggests that longer contexts may degrade few-shot performance. Additionally, streaming-based methods such as StreamingLLM(Xiao et al., 2024b) and DuoAttention(Xiao et al., 2024a) show a notable advantage on TriviaQA. Again, OracleKV demonstrates a superior accuracy–memory trade-off on both summarization and few-shot learning tasks, particularly under the 10

For passage count and passage retrieval tasks, as shown in Table A7, OracleKV delivers significant performance gains on LLaMA-3.1-8B-Instruct under both 10% and 40% KV cache budgets. For Mistral-7B-Instruct-v0.2, OracleKV outperforms all baselines on passage retrieval and achieves competitive performance with head-level methods on passage count at the

Table A4. Example of Oracle guidance. The general oracle guidance can yield improvements on most of the tasks. The task-specific oracle guidance can yield significant performance increase on corresponding tasks.

General	Next, you will be presented with a series of questions regarding the context above, including specific details about the narrative, content, and numerical information. Also, Do not forget the global information and the relations between entities. And note the structural cues. Please retain these details and provide accurate responses.
	Next, you will be presented with a series of questions regarding the context above. including specific details about the narrative, content, numerical information and key global information. The questions may also involve small fragmented relationships from the context, including term relationships, causal relations, and temporal relations. Please retain these details and provide accurate responses. Next, you will be presented with a series of questions regarding the context above. Please remember the following information: 1. specific details like names, places, and numbers; 2. main theme, like overall message; 3. relations, like family ties and event linkages, 4. semantic details, like grammar dependencies and narrative information between words.
	Analyze the given text carefully. Your tasks include: 1) Answering factual questions accurately. 2) Generating concise summaries. 3) Demonstrating in-context learning. 4) Writing code based on the text. 5) Counting paragraphs. 6) Retrieving specific strings. 7) Extracting numerical values. 8) Selecting correct answers in multiple-choice questions. 9) Calculating extreme values from arrays. Always ensure your answers are strictly based on the provided text.
	Carefully read and analyze the provided text. Your tasks involve multiple types of questions, each requiring precise information extraction from the text. Specifically, you will: 1) Answer factual questions by identifying accurate details directly from the text. 2) Generate concise and coherent summaries without introducing any external information. 3) Demonstrate in-context learning by recognizing patterns or concepts reflected in the text. 4) Write code accurately based on the textual instructions or examples. 5) Count the total number of paragraphs accurately. 6) Search and retrieve specific strings or terms mentioned in the text. 7) Extract and list numerical values, maintaining their original form. 8) Solve multiple-choice questions by selecting the most accurate answer based on the content. 9) Identify and calculate extreme values (maximum, minimum) from any given array of numbers in the text. Always ensure that your responses are strictly grounded in the provided text. Do not infer, assume, or generate information beyond what is explicitly stated. Maintain clarity, accuracy, and completeness in your answers. Stay focused on the input context and prioritize factual consistency.
Task-specific	Next, you will be asked with some questions about the context above. These questions includes: question answering, summarization, code completion, in-context learning, paragraph counting, retrival, etc. Please remember the relevant information and answering the question.
	Next, you will be asked with some questions about the context above. These questions will ask you to summarize the above context includes: question answering, summarization, code completion, in-context learning, paragraph counting, retrieval, etc. Please remember the relevant information and answering the question.
	Next, you will be asked to write a summary of all the contexts above. Please take care of the global information.
	Next, you will be asked to find a special number in the context above. Please take care of the relevant information.

Table A5. Detailed results of LongBench (Bai et al., 2024), including Single-Document QA datasets(NartvQA, Qasper, and MF-en) and Multi-Documents QA datasets(HotpotQA, 2WikiMQA, and Musique).

Method	Budget	NartvQA	Qasper	MF-en	HotpotQA	2WikiMQA	Musique
LLaMA-3.1-8B-Instruct							
Full Cache	100%	31.99	48.20	57.18	57.56	48.92	28.19
StreamingLLM	40%	23.44	30.69	29.64	47.29	33.94	22.43
SnapKV		27.04	35.66	43.22	56.79	47.50	30.06
Ada SnapKV		27.28	39.60	44.25	56.11	50.05	30.66
PyramidKV		26.85	33.16	42.14	47.17	39.22	19.60
DuoAttention		28.55	41.08	50.68	54.80	48.91	29.24
OracleKV		29.10	42.33	51.34	58.16	48.51	32.61
Ada OracleKV		28.51	44.44	53.04	57.47	47.41	31.47
StreamingLLM	10%	20.59	18.44	22.95	37.24	22.40	14.01
SnapKV		23.64	20.77	23.29	44.62	24.22	19.87
Ada SnapKV		24.24	21.14	26.88	46.35	26.95	18.80
PyramidKV		19.63	21.45	22.89	34.25	24.28	13.36
DuoAttention		15.13	14.21	25.22	35.02	22.31	12.59
OracleKV		26.77	20.18	26.59	48.31	29.19	21.95
Ada OracleKV		28.12	23.86	34.48	50.00	29.40	22.50
Mistral-7B-Instruct-v0.2							
Full Cache	100%	20.84	29.34	45.99	35.11	20.73	16.95
StreamingLLM	40%	13.75	17.09	27.75	26.87	17.31	11.44
SnapKV		15.31	19.71	36.59	28.89	15.79	13.39
Ada SnapKV		17.29	19.07	36.39	30.74	16.16	13.24
PyramidKV		15.86	19.68	36.27	30.84	18.72	12.70
DuoAttention		11.51	9.09	25.27	21.51	15.03	6.76
OracleKV		18.61	21.21	36.24	29.84	18.71	14.70
Ada OracleKV		19.13	22.04	37.94	31.29	17.88	14.81
StreamingLLM	10%	10.01	10.55	21.02	17.82	12.33	7.41
SnapKV		12.75	9.08	23.54	20.06	12.20	8.12
Ada SnapKV		14.10	9.98	23.49	21.08	13.06	8.91
PyramidKV		10.43	9.08	24.38	21.26	12.64	7.28
DuoAttention		9.01	7.98	24.96	19.68	13.56	6.01
OracleKV		13.70	13.01	25.96	20.79	13.06	7.39
Ada OracleKV		13.85	13.65	27.49	21.31	13.36	7.59
Qwen2.5-7B-Instruct-1M							
Full Cache	100%	20.23	49.72	52.53	62.91	56.35	33.74
StreamingLLM	40%	17.37	31.62	28.82	44.61	42.68	24.66
SnapKV		24.57	38.34	38.23	58.65	47.50	34.08
Ada SnapKV		26.05	38.79	41.63	59.30	48.24	33.77
PyramidKV		17.16	27.13	29.79	47.10	37.66	23.27
OracleKV		24.88	39.55	42.67	59.58	52.34	34.36
Ada OracleKV		25.08	40.32	44.64	60.07	53.86	34.87
StreamingLLM	10%	13.20	18.51	21.32	32.83	32.40	13.54
SnapKV		19.78	15.95	24.83	41.15	30.89	23.40
Ada SnapKV		22.44	17.91	25.89	42.57	31.27	22.52
PyramidKV		16.93	16.18	24.69	36.70	31.01	15.76
OracleKV		24.99	18.88	31.39	51.31	33.96	27.68
Ada OracleKV		24.97	20.73	30.33	47.04	35.03	28.94

Table A6. Detailed results of LongBench (Bai et al., 2024), including Summarization datasets(Gov Report, QMSum, Multi News) and Few-shot Learning datasets(TREC, Trivia QA, and SAMSum).

Method	Budget	GovReport	QMSum	MultiNews	TREC	TriviaQA	SAMSum
LLaMA-3.1-8B-Instruct							
Full Cache	100%	35.49	25.06	27.15	28.00	86.21	39.16
StreamingLLM	40%	30.41	21.69	24.97	31.50	91.40	37.21
SnapKV		30.96	23.37	25.07	34.50	85.13	41.04
Ada SnapKV		30.98	23.47	25.64	38.00	86.38	41.05
PyramidKV		29.72	22.65	24.86	49.00	86.28	30.76
DuoAttention		30.70	25.00	24.80	34.00	90.19	36.21
OracleKV		32.78	24.11	25.39	35.00	86.28	40.57
Ada OracleKV		32.85	24.40	25.64	33.50	87.21	39.49
StreamingLLM	10%	24.81	19.10	20.09	28.00	90.66	34.38
SnapKV		25.21	20.04	19.91	34.00	82.21	38.64
Ada SnapKV		25.57	20.87	20.52	33.00	82.88	39.18
PyramidKV		24.84	20.13	19.98	34.00	85.38	36.05
DuoAttention		23.70	17.70	22.83	25.00	86.92	36.21
OracleKV		27.61	21.28	21.45	45.50	84.11	39.31
Ada OracleKV		27.90	21.97	21.44	49.50	85.59	39.67
Mistral-7B-Instruct-v0.2							
Full Cache	100%	32.13	24.15	26.81	50.75	76.14	39.32
StreamingLLM	40%	30.23	21.34	24.54	49.50	52.78	36.48
SnapKV		28.77	22.12	24.65	44.75	77.92	39.11
Ada SnapKV		27.73	22.37	24.53	44.15	77.10	39.10
PyramidKV		28.43	22.21	24.55	45.75	79.23	39.12
DuoAttention		23.79	20.35	23.04	24.62	72.36	35.08
OracleKV		30.28	23.38	25.35	44.05	78.06	38.80
Ada OracleKV		30.03	23.31	25.36	45.25	77.17	38.78
StreamingLLM	10%	24.72	20.25	19.00	34.50	45.69	35.49
SnapKV		24.39	20.04	20.86	31.75	78.81	37.99
Ada SnapKV		24.06	20.56	20.44	37.50	79.14	38.18
PyramidKV		23.97	20.05	20.64	31.75	78.93	36.82
DuoAttention		20.89	18.38	21.87	22.62	66.06	33.69
OracleKV		26.10	21.14	22.51	32.75	77.46	36.97
Ada OracleKV		26.04	21.74	22.74	31.50	75.68	37.61
Qwen2.5-7B-Instruct-1M							
Full Cache	100%	35.45	24.59	25.97	69.50	86.53	37.21
StreamingLLM	40%	32.35	20.91	24.03	59.00	48.12	24.61
SnapKV		33.04	21.71	23.62	61.00	86.25	37.22
Ada SnapKV		32.50	21.98	23.81	64.50	86.45	36.54
PyramidKV		29.46	20.10	23.16	49.50	82.40	39.06
OracleKV		33.71	23.14	23.64	69.00	86.52	38.40
Ada OracleKV		33.51	23.50	23.84	72.00	86.88	36.44
StreamingLLM	10%	26.66	19.25	18.46	47.00	40.82	20.98
SnapKV		27.51	18.88	19.01	42.25	86.42	35.84
Ada SnapKV		27.65	18.63	19.37	45.50	85.97	36.09
PyramidKV		26.40	18.45	19.36	42.50	85.16	35.31
OracleKV		29.50	20.68	19.66	61.50	86.16	35.51
Ada OracleKV		29.43	20.58	19.81	58.25	85.68	35.46

Table A7. Detailed results of LongBench (Bai et al., 2024), including Sythetic datasets(Passage Count, Passage Retrieval) and Code Generation datasets(Lcc and RepoBench-P).

Method	Budget	Passage Count	Passage Retrieval	Lcc	RepoBench-P
LLaMA-3.1-8B-Instruct					
Full Cache	100%	11.20	100.00	54.09	47.28
StreamingLLM	40%	6.70	45.50	50.63	49.28
SnapKV		11.05	98.00	53.23	47.52
Ada SnapKV		11.55	97.00	48.21	42.85
PyramidKV		9.22	93.75	56.77	56.93
DuoAttention		6.00	99.50	55.09	53.09
OracleKV		12.65	99.50	48.35	43.89
Ada OracleKV		12.15	99.50	50.23	46.10
StreamingLLM	10%	4.00	16.00	52.29	52.88
SnapKV		5.00	54.00	51.04	48.78
Ada SnapKV		7.00	56.00	46.36	44.92
PyramidKV		7.50	46.75	51.40	52.26
DuoAttention		6.00	50.00	55.09	53.09
OracleKV		11.10	79.50	38.73	43.05
Ada OracleKV		9.50	89.00	36.76	43.72
Mistral-7B-Instruct-v0.2					
Full Cache	100%	2.81	74.17	51.25	50.74
StreamingLLM	40%	2.14	31.01	43.95	46.21
SnapKV		3.37	72.40	48.54	48.49
Ada SnapKV		3.23	67.87	48.41	48.35
PyramidKV		3.36	64.54	51.56	50.83
DuoAttention		2.08	10.54	45.24	47.28
OracleKV		3.41	71.02	46.66	47.14
Ada OracleKV		2.63	72.93	45.93	48.21
StreamingLLM	10%	3.64	10.20	46.05	47.29
SnapKV		3.16	42.77	49.31	50.06
Ada SnapKV		3.26	50.02	47.24	48.35
PyramidKV		4.41	38.83	48.81	50.73
DuoAttention		1.88	8.64	42.78	48.46
OracleKV		3.87	49.93	37.99	47.92
Ada OracleKV		3.97	61.20	38.44	47.28
Qwen2.5-7B-Instruct-1M					
Full Cache	100%	8.50	99.00	63.14	59.08
StreamingLLM	40%	5.00	34.00	56.46	54.51
SnapKV		8.50	98.00	62.13	57.71
Ada SnapKV		9.00	99.00	59.83	55.30
PyramidKV		8.50	63.00	61.76	58.54
OracleKV		9.50	98.00	55.64	56.65
Ada OracleKV		8.00	98.00	54.31	56.25
StreamingLLM	10%	2.50	10.50	55.10	54.96
SnapKV		4.50	40.50	57.98	56.39
Ada SnapKV		4.50	36.50	55.61	53.42
PyramidKV		4.50	31.00	57.92	56.47
OracleKV		9.00	71.00	43.89	55.60
Ada OracleKV		8.00	75.00	42.59	54.68

40% budget. On Qwen2.5-7B-Instruct-1M, OracleKV surpasses most methods at 40% for both passage count and retrieval tasks, and outperforms all baselines under the 10% KV cache budget for both tasks.

Table A7 highlights the side effect of OracleKV on code generation tasks, specifically on LCC and RepoBench-P. Notably, OracleKV introduces significant performance degradation on these tasks, with the most pronounced drop observed on the LCC dataset.

We hypothesize that this degradation stems from the oracle-guided attention redistribution, which may interfere with the inherent structural and syntactic regularity of code. Unlike natural language, code relies heavily on precise token dependencies and hierarchical structures. The intervention of OracleKV, though beneficial for semantic understanding tasks, may distort these structural patterns, leading to suboptimal generation quality in code-oriented scenarios.

G.3.2. Supplementary Results for RULER

We present the extended results on RULER(Hsieh et al., 2024) in TableA8, Table A9, Table A10, and Table A11. These tables report performance across 8 tasks from 13 datasets, evaluated under varying KV cache budgets (from 100% down to 10%) using two models: LLaMA-3.1-8B-Instruct and Qwen2.5-7B-Instruct-1M.

As shown in Table A8 and Table A9, OracleKV achieves a favorable accuracy–memory trade-off on the single-key Needle-in-a-Haystack (NIAH) task, demonstrating strong retrieval capabilities on both models. However, for multi-key NIAH, OracleKV shows noticeable performance degradation when compared to Ada SnapKV(Feng et al., 2024) and StreamingLLM(Xiao et al., 2024b). That said, the performance gap narrows as the KV cache budget decreases, indicating OracleKV's stronger adaptability under constrained memory conditions.

Table A9 and Table A11 further demonstrate OracleKV's strength in multi-value and multi-query variants of the NIAH task, as well as in variable tracing tasks. In these settings, OracleKV significantly outperforms all baselines across various KV cache budgets. Notably, under a 10% KV cache budget, OracleKV achieves average scores of 72.7 on LLaMA and 34.1 on Qwen, far surpassing the best-performing baselines (averaging 22.0 on LLaMA and 15.1 on Qwen). These results underscore OracleKV's effectiveness in complex retrieval and memory-intensive tasks, even under extreme memory constraints.

However, OracleKV also exhibits certain side effects on the RULER benchmark. Specifically, in word extraction (e.g., identifying the most frequently occurring words) and QA-style tasks, OracleKV underperforms relative to baseline methods, as shown in Table A9 and Table A11. This degradation suggests that OracleKV struggles with counting-oriented tasks or frequency-based reasoning. A possible explanation is that the general-purpose oracle guidance used by OracleKV does not effectively capture the inductive biases required for such tasks—biases that are rarely emphasized in large scale dialogues.

G.4. Supplementary Ablation Results

We explore the design choices of OracleKV under a question-dependent setting. As shown in Table A12, OracleKV yields small but consistent improvements over question-independent KV cache eviction when guided only by surface-level oracle guidance. This suggests that OracleKV can introduce a useful inductive bias, even when the question is already known. Additionally, as the KV cache budget decrease, OracleKV can enhance the average performance significantly (77.50 *vs.* 72.95 under 10% KV budget)

H. Supplementary Analysis

H.1. Visualization of Attention Distribution

Our main paper (Section 4) highlights the mismatch in attention distributions induced by the question and the pure context, which leads to discrepancies in the indices of retained tokens. In this section, we further investigate the differences in attention distribution and token retention across **layers** and **tasks**.

Layer-wise visualization. We observe a clear layer-wise pattern in the attention distributions. As shown in Figures A1–A14, the distributions induced by the question and pure context exhibit substantial overlap in the first three layers (Layers 0, 1, and 2) across various tasks. Notably, the attention distribution in the first layer appears relatively stable, and its attention scores are significantly higher than those in other layers.

Task-wise visualization. We also observe clear task-specific patterns in the attention distributions. Figures A1–A14 demonstrate that the overlap between attention scores induced by the question and pure context are higher in tasks such as

Table A8. Detailed results of RULER (Hsieh et al., 2024) on Llama-3.1-8B-Instruct, including the NIAH-Single and NIAH-MultiKey, both of which consists of three datasets.

Method	Budget	NIAH-Single			NIAH-MultiKey		
		S-1	S-2	S-3	MK-1	MK-2	MK-3
LLaMA-3.1-8B-Instruct							
Full Cache	100%	100.00	100.00	100.00	99.80	100.00	99.80
H2O	90%	84.00	74.20	34.60	97.40	100.00	91.40
StreamingLLM		92.60	91.60	91.40	89.00	93.60	92.20
SnapKV		99.20	100.00	21.00	99.60	98.20	83.80
PyramidKV		70.20	100.00	21.40	99.20	96.60	83.00
Ada SnapKV		100.00	100.00	65.00	99.80	100.00	99.00
OracleKV		100.00	100.00	100.00	99.80	91.20	76.20
H2O	75%	76.60	47.80	18.00	86.60	94.00	48.60
StreamingLLM		75.20	75.20	75.00	77.40	78.20	74.40
SnapKV		99.60	99.80	11.20	99.00	84.20	55.20
PyramidKV		71.00	100.00	11.20	98.60	84.20	51.00
Ada SnapKV		99.80	100.00	18.80	99.80	99.20	91.60
OracleKV		100.00	100.00	98.40	99.80	68.00	24.00
H2O	50%	46.20	23.60	11.40	51.00	46.40	15.20
StreamingLLM		50.20	50.00	55.40	55.60	49.80	48.80
SnapKV		95.40	95.20	5.60	85.40	53.60	20.60
PyramidKV		74.80	98.00	4.20	83.40	55.80	17.20
Ada SnapKV		99.00	98.60	7.60	88.80	82.80	47.40
OracleKV		100.00	100.00	49.80	99.80	26.60	2.00
H2O	40%	34.00	16.20	8.80	33.60	28.00	9.40
StreamingLLM		40.80	41.80	43.40	46.80	38.80	39.20
SnapKV		90.60	83.00	3.80	68.40	39.80	9.60
PyramidKV		72.60	92.20	3.60	71.00	41.40	10.20
Ada SnapKV		97.80	90.40	4.60	71.60	67.00	31.20
OracleKV		100.00	100.00	14.80	99.80	14.80	1.00
H2O	30%	21.80	6.80	6.80	17.80	16.60	5.00
StreamingLLM		30.20	34.00	36.60	39.20	29.20	27.60
SnapKV		82.60	65.60	2.80	43.80	22.80	4.40
PyramidKV		83.80	65.80	2.80	43.60	23.40	4.00
Ada SnapKV		95.40	70.60	2.60	44.60	44.20	14.00
OracleKV		100.00	100.00	3.00	99.80	7.40	0.00
H2O	20%	13.40	2.00	4.00	7.60	8.80	2.20
StreamingLLM		19.60	22.40	23.20	27.00	19.00	17.60
SnapKV		73.40	41.40	2.40	27.20	12.00	1.00
PyramidKV		72.80	41.80	2.40	27.40	12.20	1.00
Ada SnapKV		91.80	38.80	2.40	24.80	21.60	3.60
OracleKV		100.00	100.00	0.60	96.00	4.60	0.00
H2O	10%	5.40	1.20	2.40	3.60	3.60	0.40
StreamingLLM		10.40	15.40	15.60	17.60	9.00	7.00
SnapKV		56.20	13.40	2.40	17.40	6.20	0.40
PyramidKV		56.40	13.40	2.40	17.40	6.20	0.40
Ada SnapKV		70.20	11.40	2.40	17.00	7.80	0.60
OracleKV		100.00	100.00	0.00	77.80	3.00	0.00

Table A9. Detailed results of RULER (Hsieh et al., 2024) on LLama-3.1-8B-Instruct, including the NIAH-MultiValue(MV), NIAH-MultiQuery(MQ), Varaiable Tracing(VT), Common Words Extraction(CWE), Frequent Words Extraction(FWE), Question Answering(QA-1, QA-2).

Method	Budget	MV	MQ	VT	Word Extraction		QA	
					CWE	FWE	QA-1	QA-2
LLaMA-3.1-8B-Instruct								
Full Cache	100%	99.90	99.90	99.88	99.62	94.80	87.80	62.80
H2O	90%	96.15	96.55	98.68	99.64	94.60	87.60	61.60
StreamingLLM		87.90	89.05	100.00	99.70	95.40	87.00	59.00
SnapKV		98.80	99.60	97.80	99.56	94.80	87.20	61.40
PyramidKV		99.70	99.20	97.96	99.78	94.40	80.60	54.40
Ada SnapKV		99.90	99.85	99.92	99.70	94.67	87.20	62.40
OracleKV		99.90	99.90	99.92	99.48	94.73	85.00	62.20
H2O	75%	82.70	81.75	97.40	99.66	94.27	86.80	59.80
StreamingLLM		75.35	76.20	94.68	99.62	94.07	87.00	55.00
SnapKV		90.35	96.05	93.36	99.42	94.27	83.20	58.80
PyramidKV		97.85	98.20	93.52	99.58	93.47	78.20	53.00
Ada SnapKV		98.95	99.45	99.92	99.58	94.27	84.80	59.00
OracleKV		99.85	99.90	99.92	99.00	93.47	78.60	60.00
H2O	50%	43.85	43.55	91.12	99.66	93.87	86.80	56.20
StreamingLLM		53.40	53.60	72.40	53.38	91.60	87.40	49.60
SnapKV		72.65	75.75	82.16	98.38	92.33	75.60	52.00
PyramidKV		76.80	75.85	80.68	90.26	88.93	67.20	43.80
Ada SnapKV		78.60	85.60	96.68	99.28	94.73	77.20	52.80
OracleKV		99.90	99.70	99.64	95.54	89.87	58.00	52.40
H2O	40%	23.80	25.10	85.16	99.58	93.33	85.80	52.60
StreamingLLM		43.00	43.25	62.28	26.86	91.93	87.40	47.00
SnapKV		56.15	57.85	75.12	96.34	90.87	69.20	48.60
PyramidKV		56.30	54.85	72.88	82.18	85.67	68.80	44.80
Ada SnapKV		59.65	60.55	93.28	99.06	94.47	73.20	47.20
OracleKV		98.35	99.60	98.76	91.50	87.40	49.80	47.20
H2O	30%	9.90	11.45	73.84	98.70	92.13	85.00	47.60
StreamingLLM		35.55	36.40	49.28	13.50	92.60	88.00	41.80
SnapKV		32.00	34.40	65.32	90.80	87.47	60.60	40.80
PyramidKV		31.55	34.75	65.56	90.22	87.47	60.60	40.60
Ada SnapKV		28.20	29.60	86.64	97.78	93.33	64.60	43.60
OracleKV		96.60	98.70	96.20	80.68	83.67	41.40	44.80
H2O	20%	2.30	4.90	46.28	95.46	89.60	79.00	40.80
StreamingLLM		22.85	23.25	35.96	1.60	92.80	88.60	36.40
SnapKV		20.65	21.45	51.72	73.02	81.60	48.60	34.60
PyramidKV		20.05	21.50	52.28	72.92	81.87	48.40	34.60
Ada SnapKV		17.15	19.30	67.44	93.44	90.20	55.60	36.80
OracleKV		90.55	95.05	90.68	60.62	78.27	31.20	36.40
H2O	10%	0.30	2.45	18.28	78.28	77.93	68.40	32.00
StreamingLLM		15.15	15.25	19.12	0.44	87.60	74.60	29.80
SnapKV		15.05	16.05	30.44	16.08	67.80	32.20	24.80
PyramidKV		15.00	16.20	30.68	16.40	67.67	32.00	25.00
Ada SnapKV		14.90	16.25	34.60	44.54	78.87	35.60	27.20
OracleKV		72.65	76.35	69.00	30.70	65.20	19.20	27.60

Table A10. Detailed results of RULER (Hsieh et al., 2024) on Qwen2.5-7B-Instruct-1M, including the NIAH-Single and NIAH-MultiKey, both of which consists of three datasets.

Method	Budget	NIAH-Single			NIAH-MultiKey		
		S-1	S-2	S-3	MK-1	MK-2	MK-3
Qwen2.5-7B-Instruct-1M							
Full Cache	100%	100.00	99.00	99.80	100.00	99.80	99.40
H2O	90%	39.00	98.00	13.80	86.80	80.40	84.00
StreamingLLM		32.00	96.40	9.60	77.00	73.20	70.80
SnapKV		92.00	86.40	88.60	89.00	92.40	89.60
PyramidKV		86.20	98.40	40.60	99.20	99.00	92.60
Ada SnapKV		18.00	9.60	0.20	25.40	30.40	1.20
OracleKV		100.00	98.80	96.40	99.80	22.40	44.20
H2O	75%	24.80	79.80	6.20	55.60	61.40	39.80
StreamingLLM		17.60	59.40	3.40	37.00	44.60	23.20
SnapKV		75.00	74.40	74.60	77.40	77.80	72.80
PyramidKV		66.80	96.40	11.40	81.20	90.20	54.60
Ada SnapKV		14.60	4.40	0.20	18.80	17.40	0.20
OracleKV		100.00	99.00	70.40	97.80	3.60	12.60
H2O	50%	15.00	38.40	2.80	25.20	29.40	8.80
StreamingLLM		9.40	11.80	2.40	13.40	10.40	1.40
SnapKV		49.40	49.40	55.20	55.20	49.60	48.60
PyramidKV		31.00	58.00	4.00	37.00	45.20	12.60
Ada SnapKV		10.20	1.80	0.00	8.00	6.20	0.00
OracleKV		100.00	99.20	12.20	87.00	1.40	2.60
H2O	40%	14.00	27.40	2.60	22.60	19.60	4.40
StreamingLLM		8.40	6.60	2.40	12.00	7.00	0.60
SnapKV		40.80	41.60	43.00	46.60	38.80	38.40
PyramidKV		22.00	41.00	2.80	25.40	29.60	6.20
Ada SnapKV		8.80	1.60	0.00	3.80	0.00	9.40
OracleKV		100.00	99.80	5.80	79.20	1.20	1.40
H2O	30%	11.80	18.40	2.40	17.20	13.80	1.60
StreamingLLM		12.00	18.40	2.40	17.40	4.40	1.60
SnapKV		30.20	33.60	36.20	39.00	29.00	26.40
PyramidKV		15.60	23.00	2.60	19.40	18.40	4.60
Ada SnapKV		6.00	1.20	0.00	4.60	2.60	0.00
OracleKV		100.00	99.80	0.60	65.20	1.00	0.00
H2O	20%	11.00	10.00	2.40	12.40	7.60	0.40
StreamingLLM		10.80	10.00	2.40	12.40	7.60	0.40
SnapKV		19.60	22.20	21.60	26.80	19.00	17.40
PyramidKV		12.40	11.20	2.40	13.60	10.20	1.00
Ada SnapKV		4.00	1.00	0.00	2.40	2.00	0.00
OracleKV		100.00	99.00	0.40	46.60	1.00	0.00
H2O	10%	8.40	3.20	2.40	10.40	2.40	0.00
StreamingLLM		8.40	3.20	2.40	10.40	2.40	0.00
SnapKV		10.40	15.40	13.00	16.20	9.00	7.00
PyramidKV		7.60	2.80	2.40	10.20	3.60	0.00
Ada SnapKV		1.40	0.60	0.00	1.00	0.60	0.00
OracleKV		99.40	89.00	0.00	25.20	0.60	0.00

Table A11. Detailed results of RULER (Hsieh et al., 2024) on Qwen2.5-7B-Instruct-1M, including the NIAH-MultiValue(MV), NIAH-MultiQuery(MQ), Varaiable Tracing(VT), Common Words Extraction(CWE), Frequent Words Extraction(FWE), Question Answering(QA-1, QA-2).

Method	Budget	MV	MQ	VT	Word Extraction		QA	
					CWE	FWE	QA-1	QA-2
Qwen2.5-7B-Instruct-1M								
Full Cache	100%	99.30	99.60	99.92	95.24	85.87	85.80	60.40
H2O	90%	64.65	80.75	86.32	95.40	85.93	85.60	58.60
StreamingLLM		47.10	63.95	81.00	95.94	87.80	84.40	57.40
SnapKV		89.25	88.75	77.32	95.82	89.60	86.20	60.20
PyramidKV		91.00	96.70	98.60	95.06	85.93	85.60	58.60
Ada SnapKV		22.35	23.40	53.28	84.34	83.87	83.40	55.80
OracleKV		98.80	99.50	99.92	95.18	84.60	84.40	58.80
H2O	75%	32.90	45.85	66.76	94.98	86.33	82.80	58.20
StreamingLLM		20.40	27.10	57.96	95.20	87.20	80.20	52.80
SnapKV		75.75	75.95	78.36	94.12	88.60	86.20	55.20
PyramidKV		53.60	71.00	90.92	95.16	86.20	84.20	57.40
Ada SnapKV		14.80	16.20	49.84	83.28	83.73	82.20	53.80
OracleKV		96.60	98.25	99.92	94.40	82.27	77.60	55.40
H2O	50%	17.90	21.60	43.16	92.42	85.33	73.00	48.00
StreamingLLM		11.00	12.05	12.48	45.52	79.00	50.20	33.00
SnapKV		53.00	52.85	61.96	88.60	85.93	86.60	49.40
PyramidKV		21.95	30.40	61.24	93.70	85.67	75.80	50.80
Ada SnapKV		4.60	6.25	30.24	82.54	85.20	79.00	49.40
OracleKV		78.00	84.50	99.84	89.42	78.00	61.40	50.80
H2O	40%	14.70	17.65	39.72	89.28	84.00	68.40	46.60
StreamingLLM		10.05	10.80	10.32	42.86	77.33	64.20	36.00
SnapKV		42.70	43.10	52.12	87.62	85.93	87.40	47.00
PyramidKV		17.50	23.70	46.72	92.54	85.60	69.40	48.00
Ada SnapKV		2.70	4.50	21.56	81.34	84.07	79.20	46.20
OracleKV		68.60	74.45	99.32	84.04	76.27	55.40	48.20
H2O	30%	12.45	14.95	30.68	84.44	82.27	59.00	43.80
StreamingLLM		12.60	15.05	30.64	38.64	82.33	58.80	43.40
SnapKV		35.50	36.30	40.76	84.50	83.53	86.60	44.40
PyramidKV		13.60	16.35	32.72	88.86	84.67	61.20	43.60
Ada SnapKV		1.40	2.75	12.44	77.02	82.07	73.80	44.00
OracleKV		57.85	61.45	97.68	74.80	75.00	45.60	42.80
H2O	20%	11.25	12.65	22.44	73.58	80.33	52.00	37.00
StreamingLLM		11.25	12.60	22.08	73.80	80.40	52.20	37.20
SnapKV		22.65	23.10	29.04	80.10	83.87	87.60	37.20
PyramidKV		12.05	13.80	20.84	81.44	82.13	53.80	37.60
Ada SnapKV		0.70	1.85	9.04	69.70	77.60	72.40	40.20
OracleKV		43.10	44.75	91.56	56.32	69.40	36.60	39.00
H2O	10%	9.60	9.90	11.80	54.48	72.73	35.20	25.80
StreamingLLM		9.60	9.90	11.68	54.62	72.60	35.20	26.60
SnapKV		14.55	14.90	15.80	65.90	76.87	73.20	28.80
PyramidKV		9.55	9.90	11.52	62.22	76.93	36.20	27.60
Ada SnapKV		0.90	0.90	5.00	45.86	69.40	58.60	32.60
OracleKV		24.55	23.00	54.76	30.60	60.73	27.80	28.60

Method	Budget	Avg.Performance
SnapKV	50%	94.78
OracleKV	50%	95.26
SnapKV	20%	92.98
OracleKV	20%	93.97
SnapKV	10%	72.95
OracleKV	10%	77.50

Table A12. Question-dependent performance of OracleKV on RULER (Hsieh et al., 2024) benchmark. We use general surface-level oracle guidance.

word extraction, variable tracing, and question answering, compared to NIAH tasks.

H.2. Side Effects of OracleKV

We observe side effects of OracleKV on certain datasets across benchmarks (e.g., code generation in LongBench (Bai et al., 2024), and word extraction and QA in RULER (Hsieh et al., 2024)). However, consistent with the no-free-lunch principle, OracleKV generally performs well across a majority of tasks, serving as an effective approach for KV cache eviction.

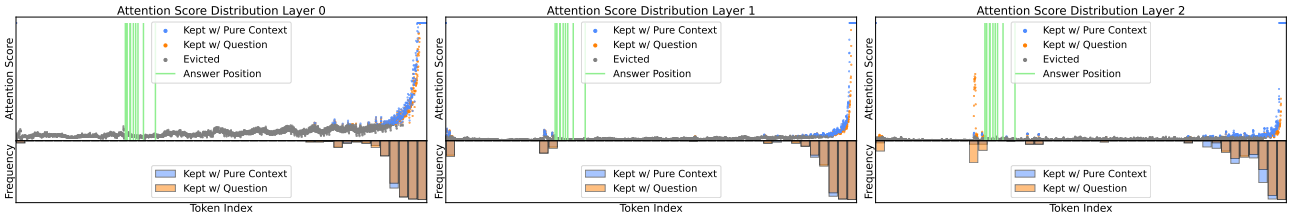

Figure A19. Attention distribution of first three layers in Common Words Extraction (CWE) task.

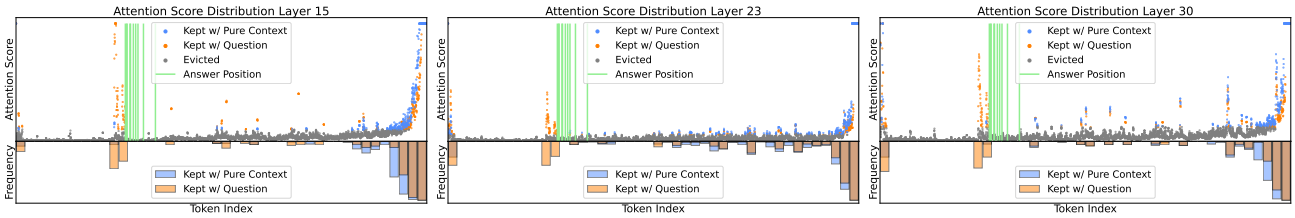

Figure A20. Attention distribution of layer 15, 23, 30 in Common Words Extraction (CWE) task.

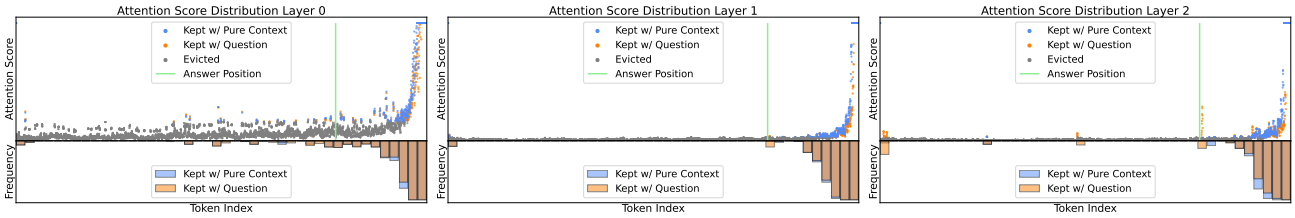

Figure A21. Attention distribution of first three layers in multi-key needle in a haystack (NIAH) task.

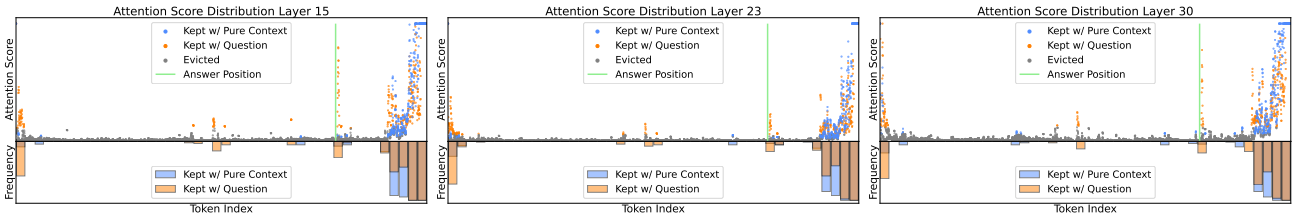

Figure A22. Attention distribution of first layer 15, 23, 30 in multi-key needle in a haystack (NIAH) task.

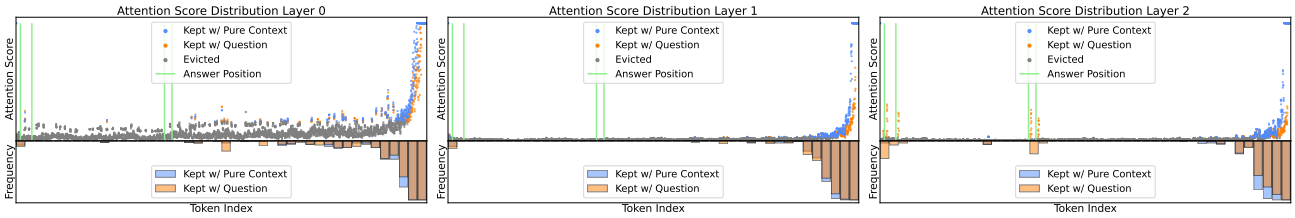

Figure A23. Attention distribution of first three layers in multi-query needle in a haystack (NIAH) task.

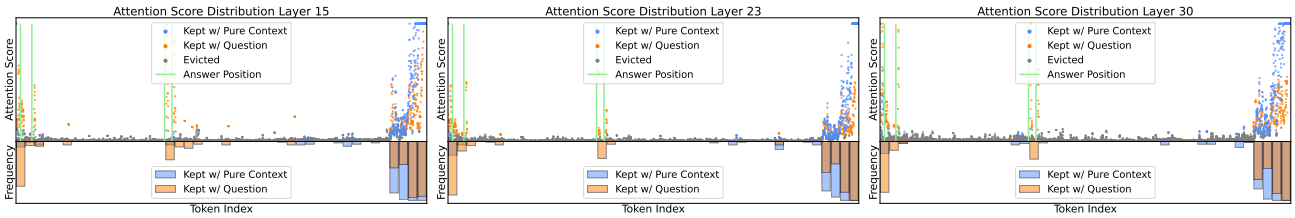

Figure A24. Attention distribution of first layer 15, 23, 30 in multi-query needle in a haystack (NIAH) task.

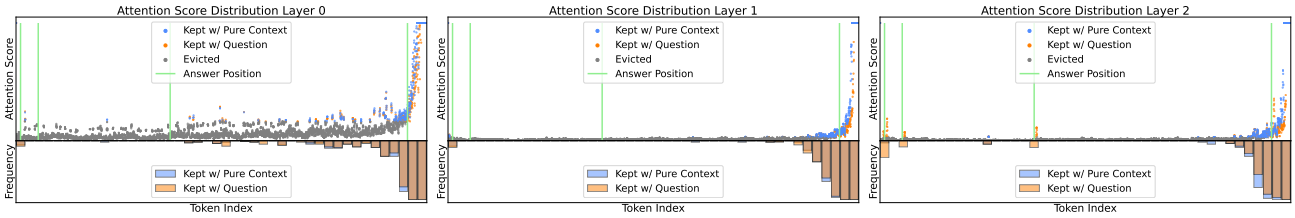

Figure A25. Attention distribution of first three layers in multi-value needle in a haystack (NIAH) task.

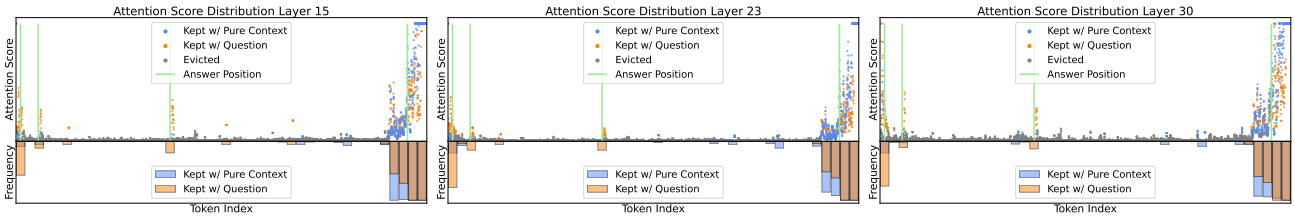

Figure A26. Attention distribution of first layer 15, 23, 30 in multi-value needle in a haystack (NIAH) task.

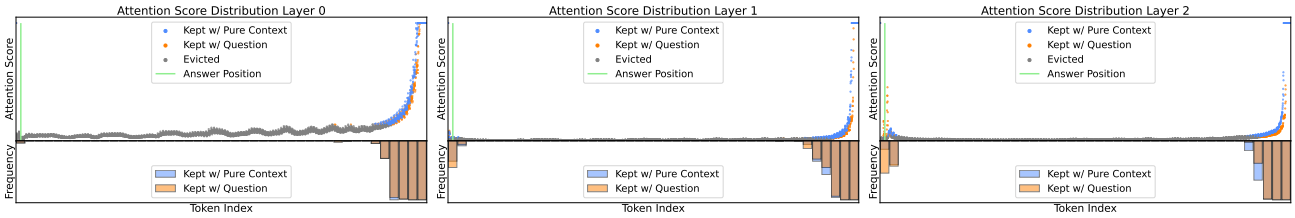

Figure A27. Attention distribution of first three layers in single needle in a haystack (NIAH) task.

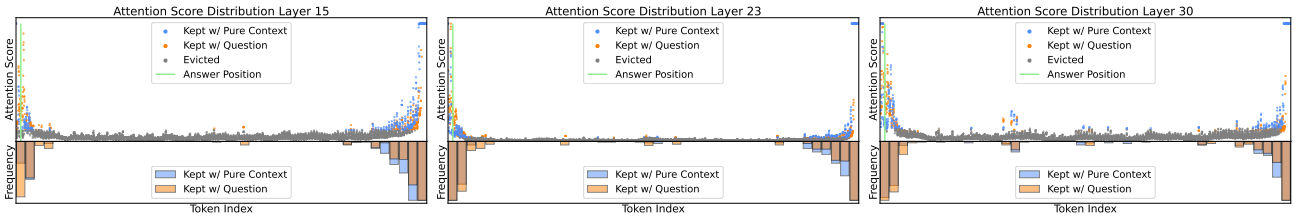

Figure A28. Attention distribution of first layer 15, 23, 30 in single needle in a haystack (NIAH) task.

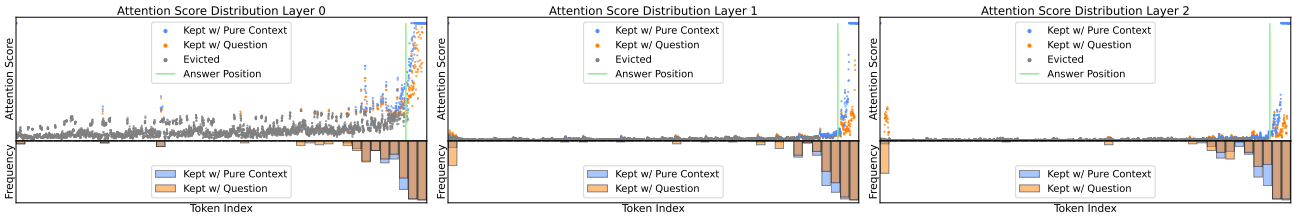

Figure A29. Attention distribution of first three layers in question-answering (QA) task.

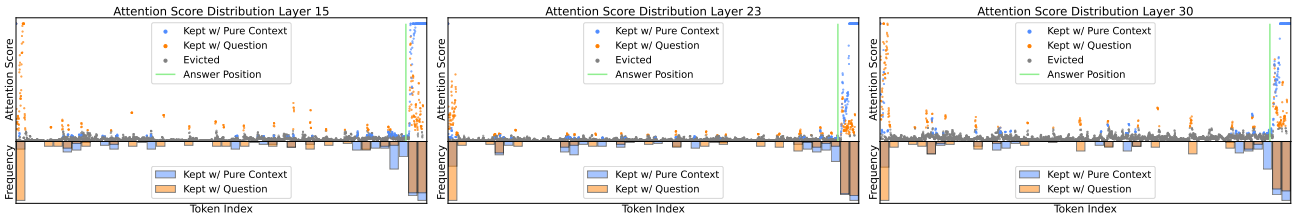

Figure A30. Attention distribution of first layer 15, 23, 30 in question-answering (QA) task.

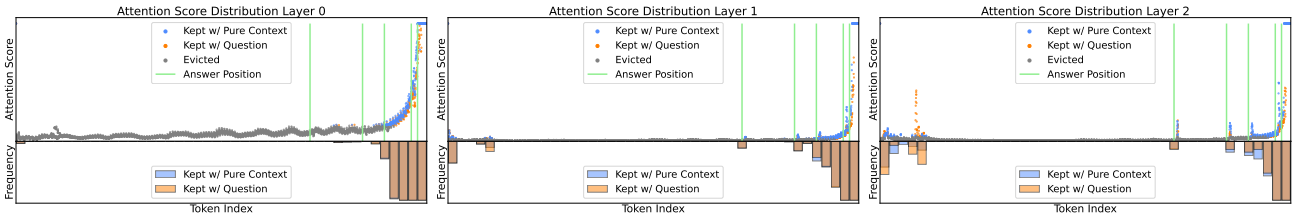

Figure A31. Attention distribution of first three layers in variable tracing (VT) task.

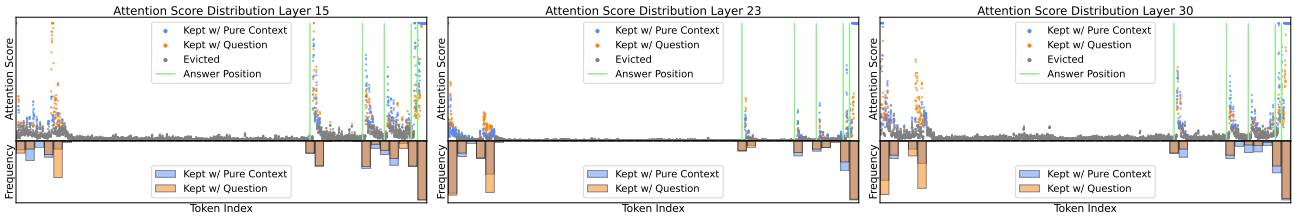

Figure A32. Attention distribution of first layer 15, 23, 30 in variable tracing (VT) task.

I. More Related Work

I.1. KV Cache Eviction

Previous research has highlighted the inherent sparsity in the self-attention mechanisms of large language models (LLMs). Leveraging this property, early studies (Liu et al., 2024b; Zhang et al., 2023) propose maintaining a queue with a pre-allocated budget and progressively evicting unimportant cache entries during the inference. Subsequent works focus on exploiting fixed attention patterns within the input sequence. StreamingLLM (Xiao et al., 2024b) and LM-Infinite (Han et al., 2024) utilize the *attention sink* phenomenon to retain both initial and most recent tokens. Recently, SnapKV (Li et al., 2024a) introduces an attention-based strategy that uses attention scores with recent tokens to estimate importance. Building on this foundation, several approaches (Hao et al., 2025; Qin et al., 2025; Cai et al., 2024; Yang et al., 2024c) incorporate layer-wise cache budget allocation. PyramidKV (Cai et al., 2024) and PyramidInfer (Yang et al., 2024c) discard more KV entries from deeper layers, motivated by the *pyramidal information funneling* hypothesis. Similarly, CAKE (Qin et al., 2025) analyzes layer-wise preferences using spatial and temporal attention dynamics to optimize cache retention. In parallel, the discovery of *retrieval heads* in attention mechanisms (Wu et al., 2024) fuel a new line of research in head-level cache eviction (Fu et al., 2024; Xiao et al., 2024a; Feng et al., 2024). DuoAttention (Xiao et al., 2024a) employs a learning-based method to identify *compression-insensitive* attention heads (*i.e.*, streaming heads), while HeadKV (Fu et al., 2024) classifies heads based on their retrieval and reasoning utility (R2 heads).

Most recent research has introduced a variety of strategies for managing the Key-Value (KV) cache in large language models (LLMs), focusing on eviction and compression techniques to enhance memory efficiency without compromising performance. Eviction methods like NaCl (Chen et al., 2024) combine attention-based statistics with randomized strategies to retain crucial tokens, achieving significant cache reduction while maintaining high performance. HashEvict (Liu et al., 2024a) employs locality-sensitive hashing to identify and replace tokens with low relevance, reducing computational overhead. Compression approaches have also evolved; GEAR (Kang et al., 2024) integrates ultra-low precision quantization, low-rank approximation, and sparse matrices to achieve near-lossless 4-bit compression, enhancing throughput. RazorAttention (Tang et al., 2024) differentiates between retrieval and non-retrieval heads, maintaining full cache for the former while discarding distant tokens for the latter. FastGen (Jacobs et al., 2023) introduces a plug-and-play adaptive compression method that profiles attention modules to selectively retain or discard tokens based on their contextual importance, significantly reducing GPU memory usage. Additionally, methods like BalanceKV (Han et al., 2025) utilize vector balancing theory for geometric sampling, and LoRC (Zhang et al., 2024) applies low-rank approximations with progressive compression strategies. These methodologies collectively advance the efficiency of LLM inference by intelligently managing KV cache resources.

Despite these approaches achieve impressive performance on several long-context benchmarks, most existing methods (*e.g.* (Li et al., 2024a; Cai et al., 2024; Yang et al., 2024c; Qin et al., 2025; Feng et al., 2024; Fu et al., 2024; Hao et al., 2025)) rely heavily on importance metrics derived from the attention scores with the current question, limiting their robustness and applicability in real-world scenarios without question. In contrast, our approach operates at the data level, leveraging surface-level statistical regularities in the question distribution, making it compatible with existing methods and easily integrable into a broader range of applications.

I.2. In-Context Learning

Early studies (Devlin et al., 2019; Liu et al., 2019) observed that language models can ”learn” to perform a task from a few shot input-output examples provided in context at inference. (Xie et al., 2021) interprets the emergence of in-context learning by inferring the shared latent concept among demonstration examples. Based on these, OracleKV affects the attention behavior through in-context data manipulation, aiming to select instruction-correlated tokens.

Recently, (Bai et al., 2023) provided theoretical evidence that transformers can implement a broad class of machine learning algorithms in-context, including least squares and Lasso, and can adaptively select among them based on input sequences. Further empirical analysis (Kossen et al., 2023) revealed that ICL predictions are heavily influenced by in-context labels and that models can learn novel tasks in-context, although they may retain biases from pre-training data. For the algorithmic reasoning, (Zhou et al., 2022) introduced *algorithmic prompting*, teaching LLMs to perform multi-step reasoning tasks by formulating algorithms as composable skills, leading to significant performance improvements. Additionally, (Kirsch et al., 2022) explored meta-learning approaches, showing that transformers can be trained to act as general-purpose in-context learners, capable of adapting to diverse tasks without explicit training loss definitions.

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