An I/O Characterizing Study of Offloading LLM Models and KV Caches to NVMe SSD

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Background

LLM-based applications are becoming widely used.

ChatGPT
deepseek
Gemini
Claude
IBM
Llama 3
Granite

High memory cost

Model	Model Size (FP8)
Mistral-Large	123 GiB
GPT3-175B	175 GiB
OPT-175B	175 GiB
Llama3-405B	405 GiB

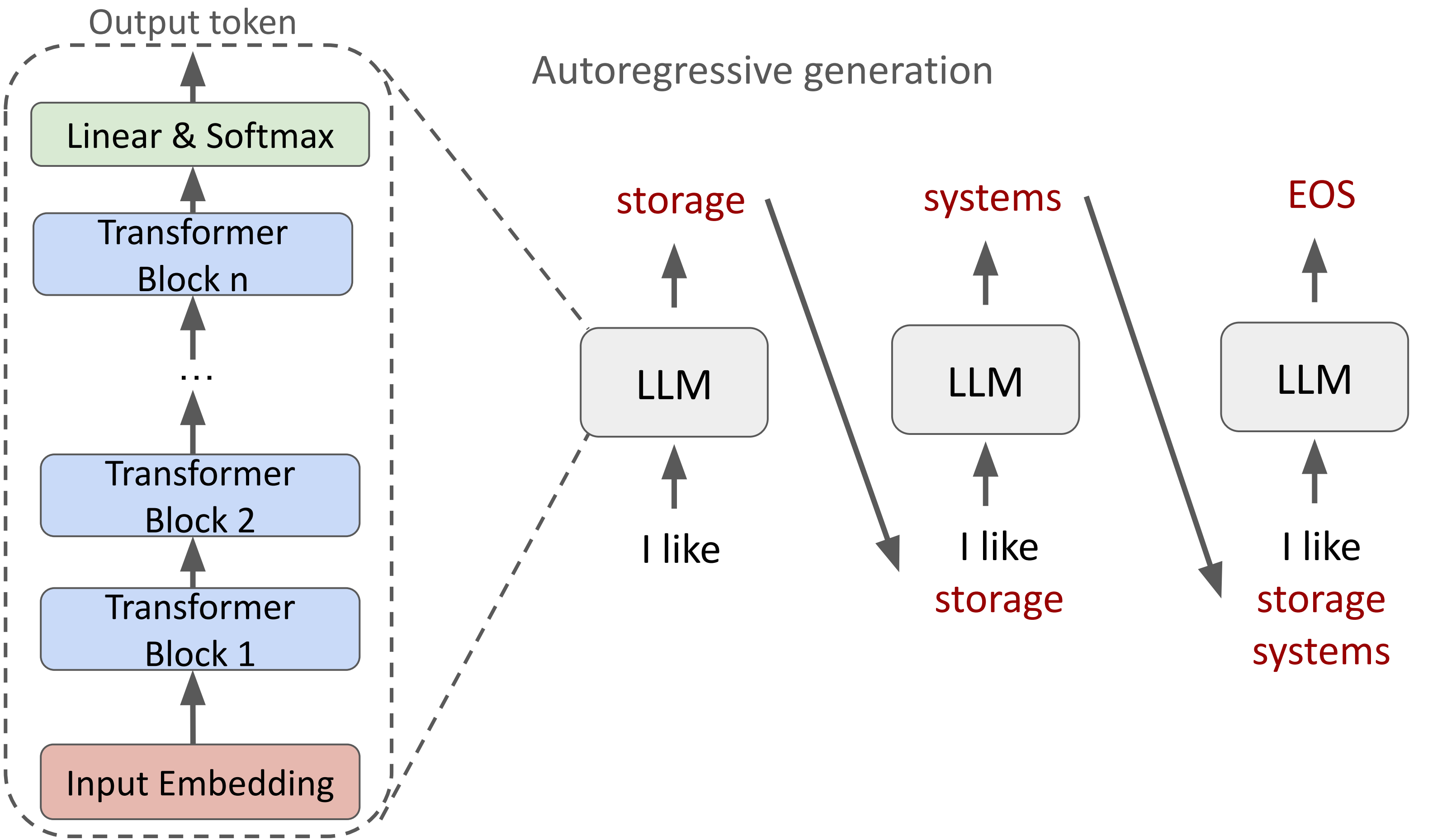
Modern LLMs fail to fit into a single GPU memory.

Solution:

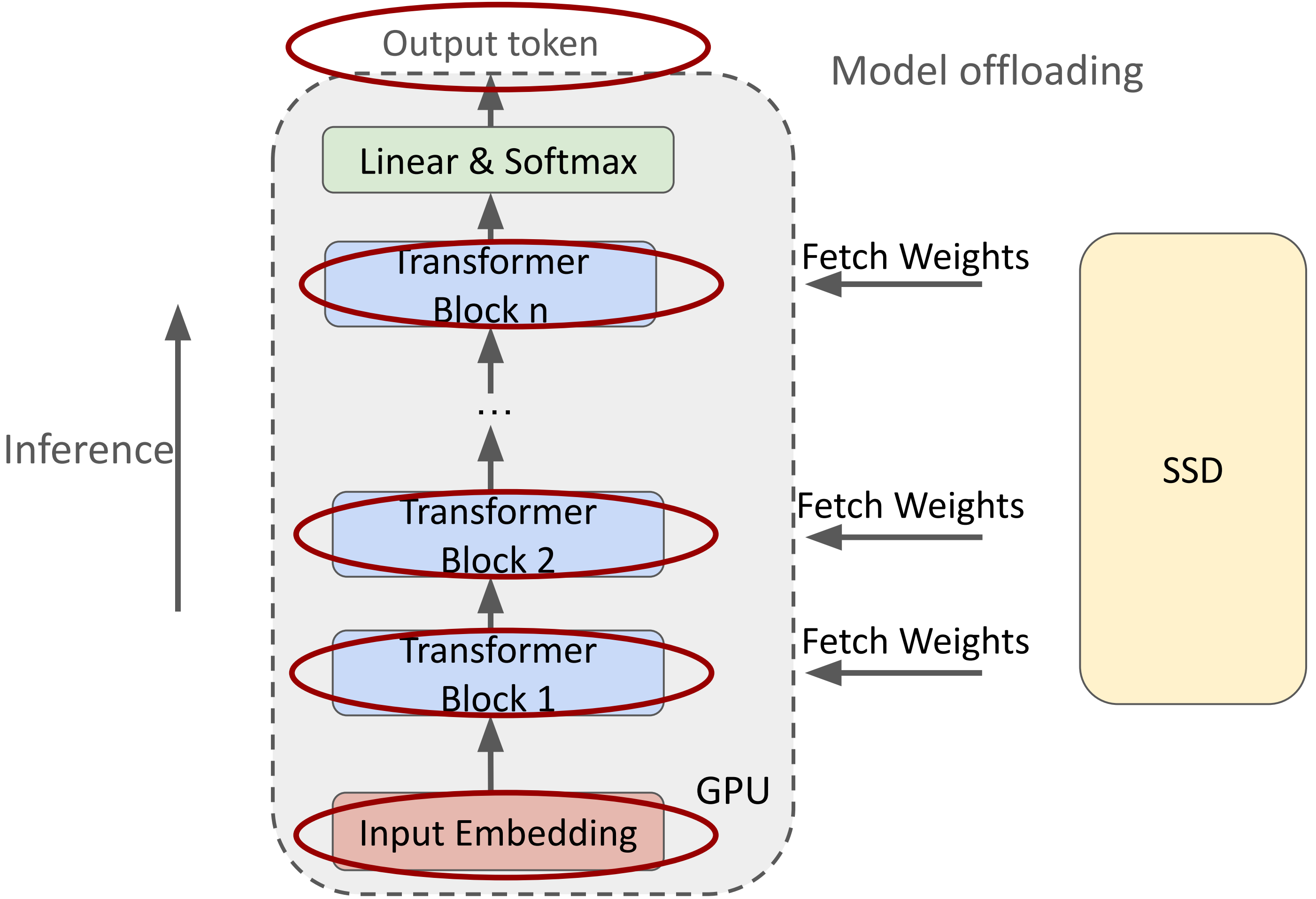
- Parallelism with multiple GPU.
- Quantization and sparsity.
- Compression.
- Model offloading.
- …

This work: Offloading the GPU usage to SSD during LLM inference.

Offloading During LLM Inference



Offloading During LLM Inference



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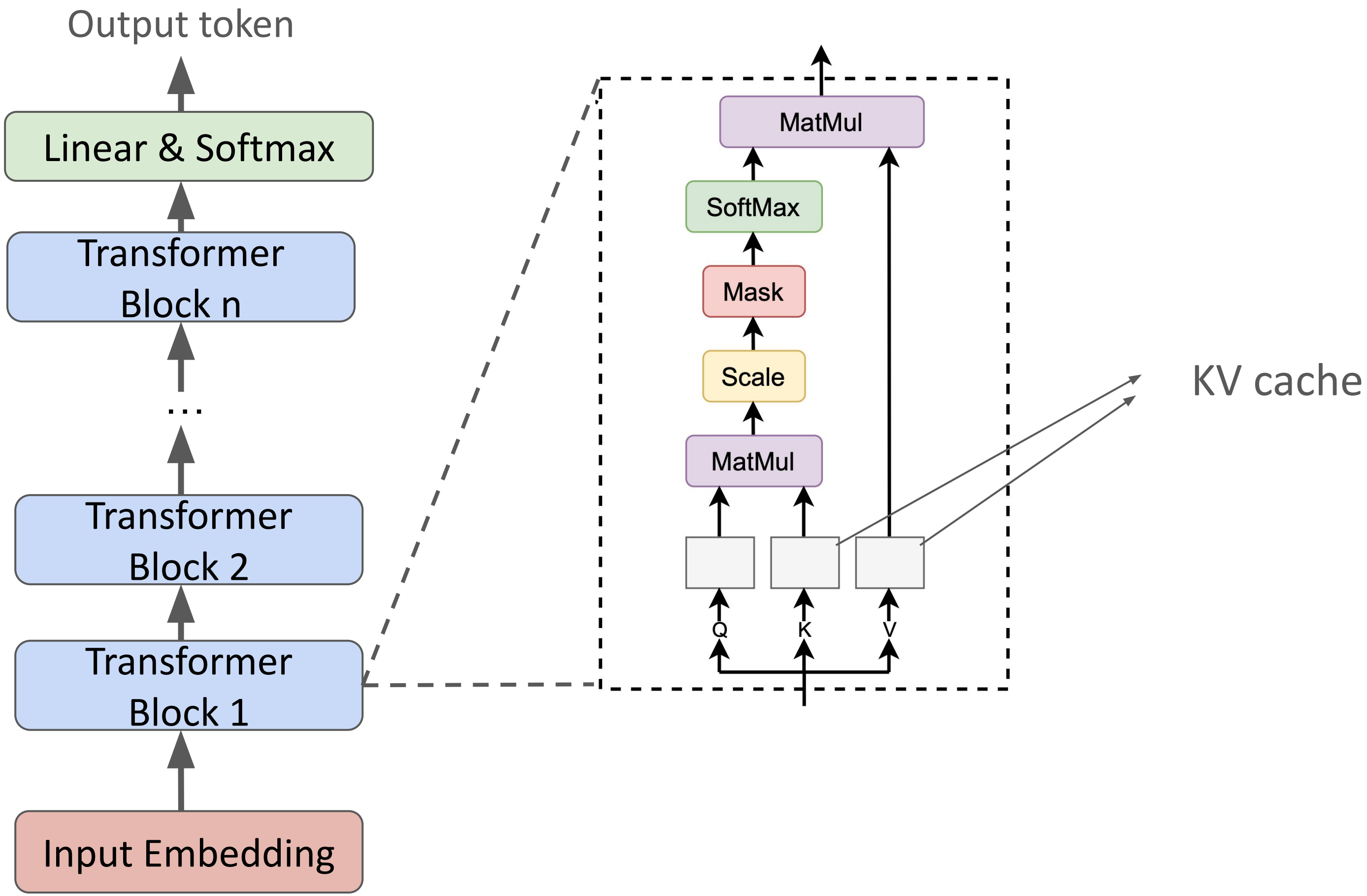

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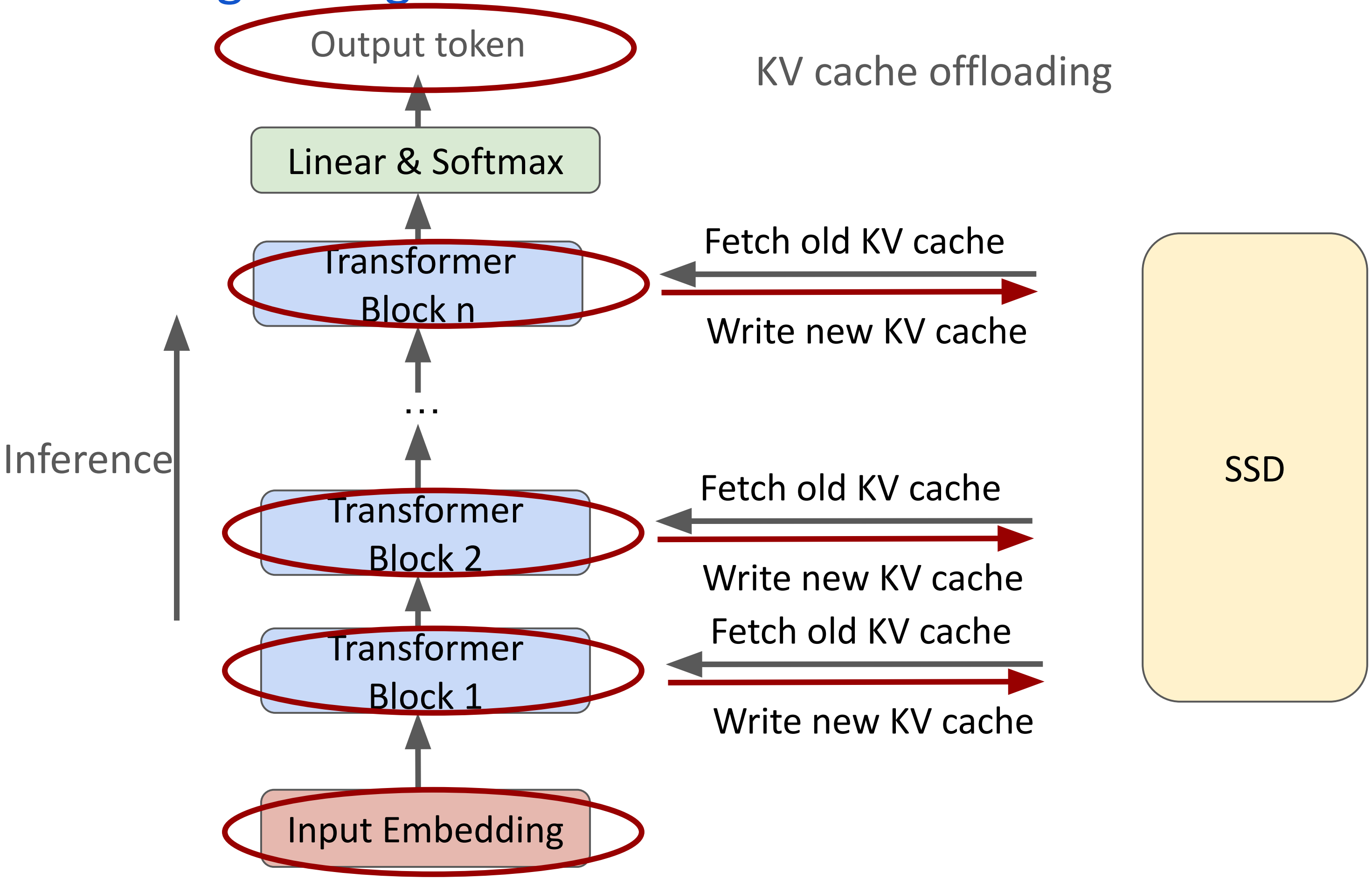
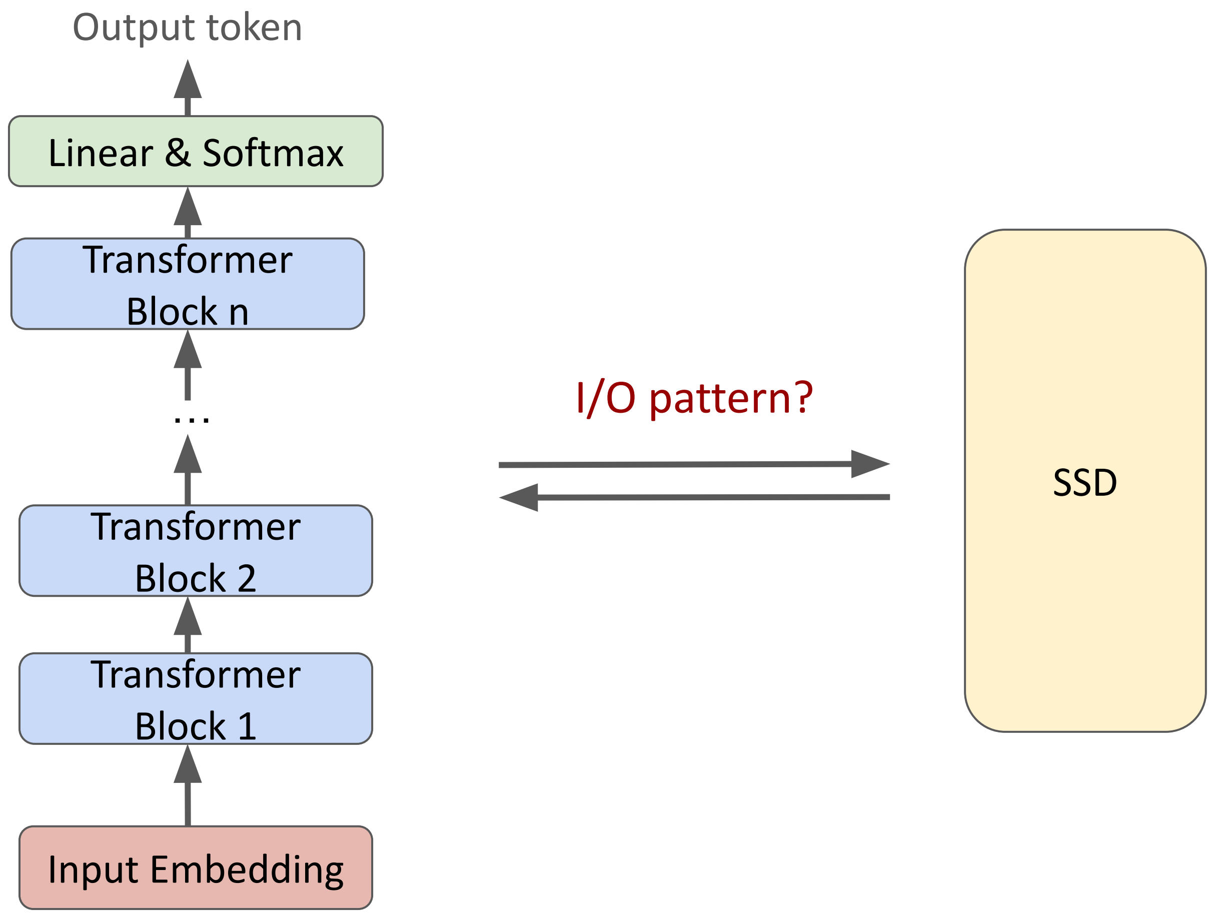


Offloading During LLM Inference



Research Questions

Q1: What is the tensor (model weights and KV cache) transferring bandwidth between the CPU/GPU memory and the SSDs?

- DeepNVMe — An I/O library for deep learning.
- Two interfaces: POSIX and libaio.

Q2: What are the I/O access patterns of model offloading?

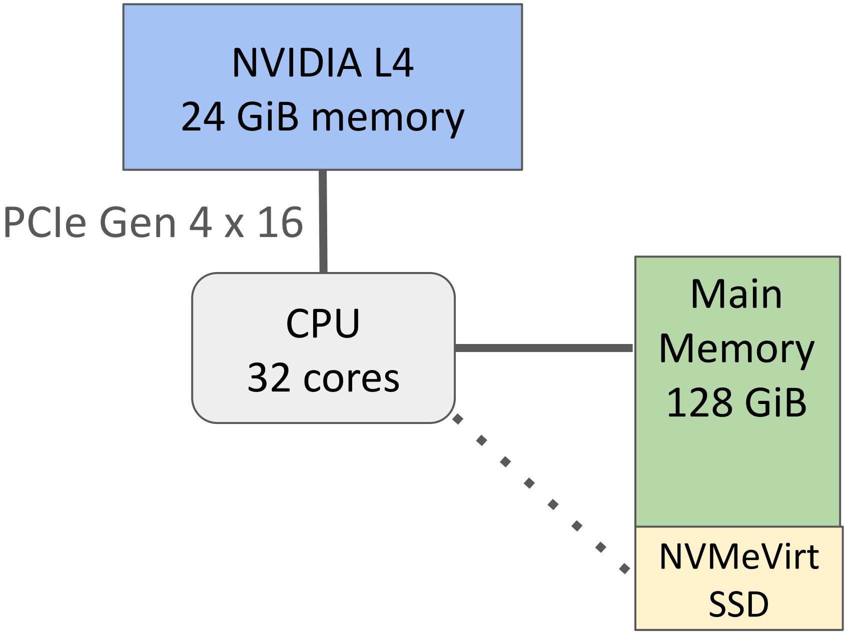
- DeepSpeed and FlexGen.
- Offload the model to NVMe disk and keep all other data in GPU.

Q3: What are the I/O access patterns of KV cache offloading?

- FlexGen.
- Offload the KV cache to NVMe disk and keep all other data in GPU.

Experiment Setup

Hardware



Software

NVMeVirt (SSD emulator)

- 4 CPU cores
- 5.3 GiB/s@512KiB with 1 thread
- 16.9 GiB/s@512KiB with 4 threads

LLM I/O library:

- DeepNVMe

LLM framework:

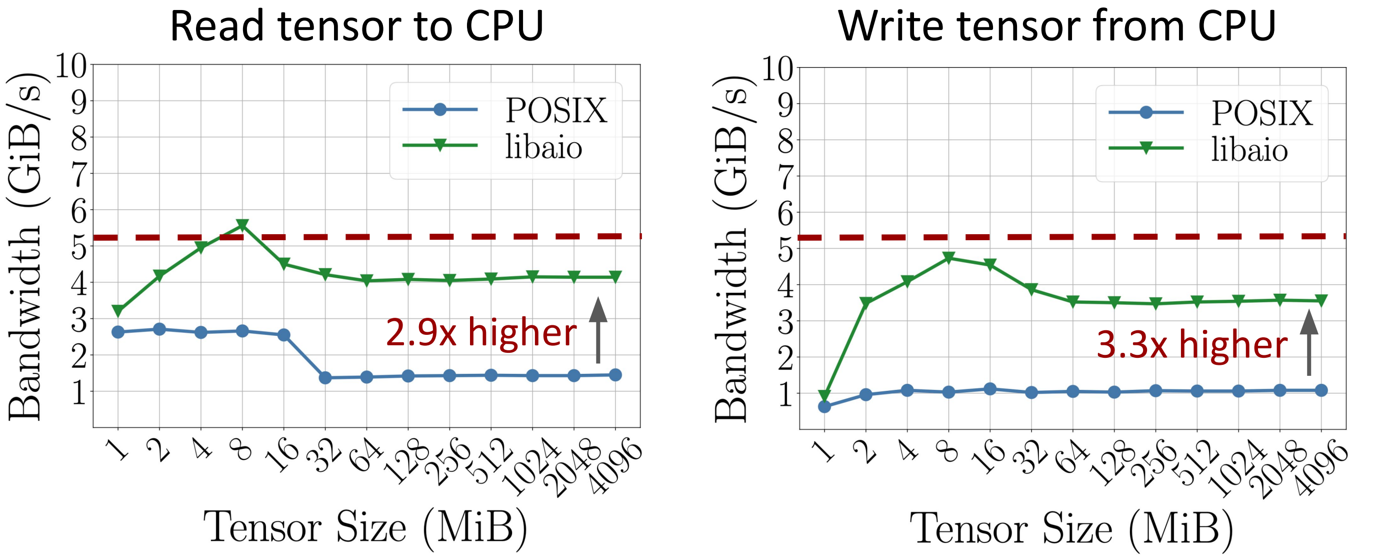
- DeepSpeed Inference
- FlexGen

LLM models:

- OPT 6.7B, 13B and 30B with FP16 quantization

Q1: Tensor transferring bandwidth between the CPU/GPU memory and the SSDs.

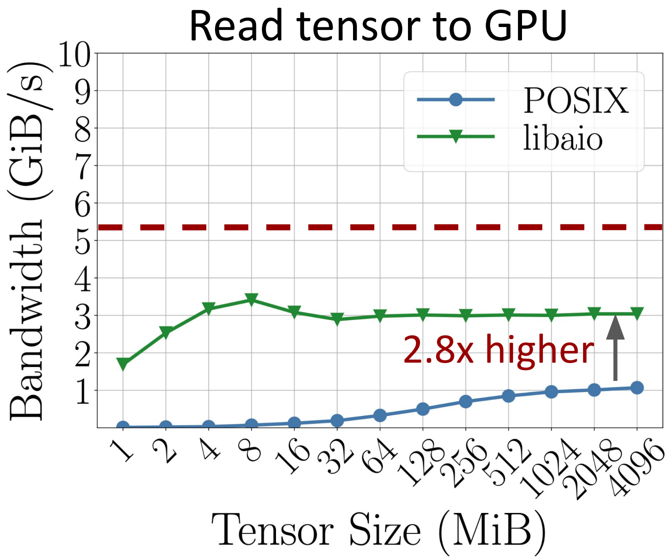
Transferring Tensors with DeepNVMe

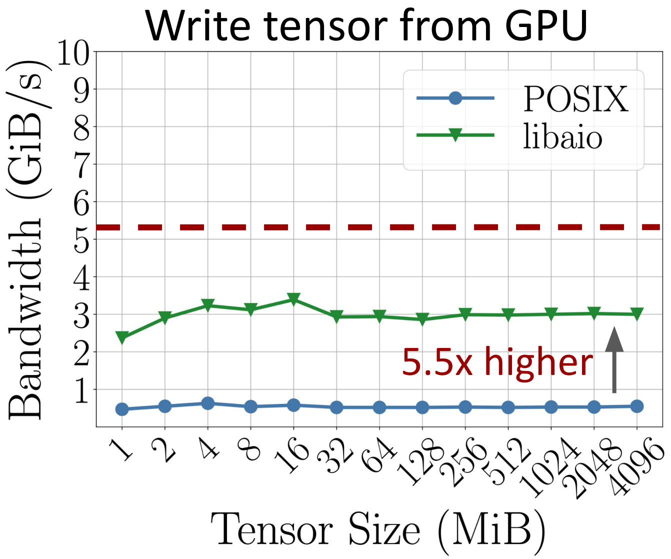


libaio delivers up to 2.9×, 3.3× higher bandwidth than POSIX for reading tensors to CPU, writing tensors from CPU.

Neither POSIX or libaio can reach the single-thread bandwidth of the NVMe SSD (5.3 GiB/s).

Transferring Tensors with DeepNVMe



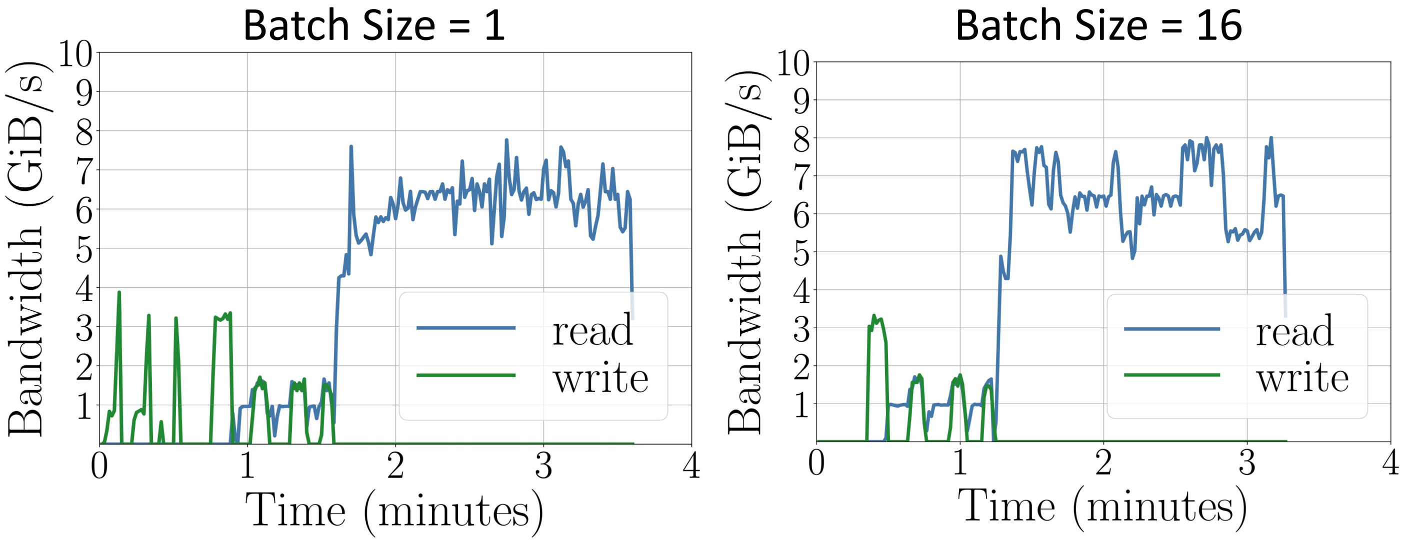


libaio delivers up to 2.8×, 5.5× higher bandwidth than POSIX for reading tensors to GPU, writing tensors from GPU.

Transferring tenser between GPU and SSD achieves lower bandwidth than transferring tenser between CPU and SSD.

Q2: I/O access patterns of model offloading.

Model offloading with DeepSpeed (OPT-13B)



The model is offloaded once and then read-only.

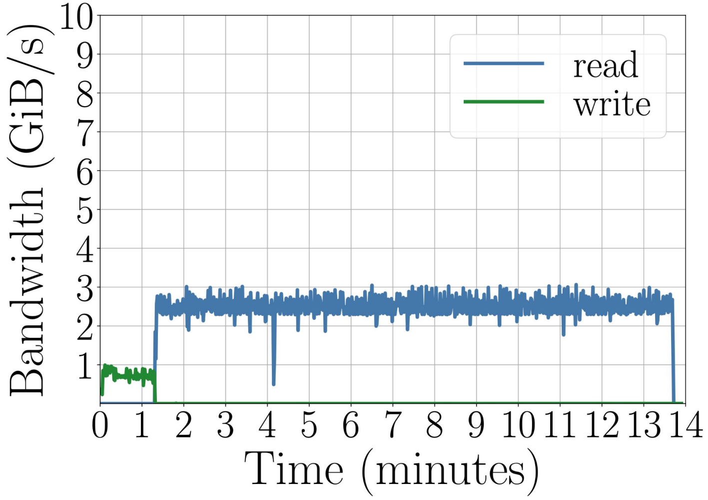
The batch size does not lead to increased I/O traffic.

The block-level I/O is dominated by 128 KiB reads and writes.

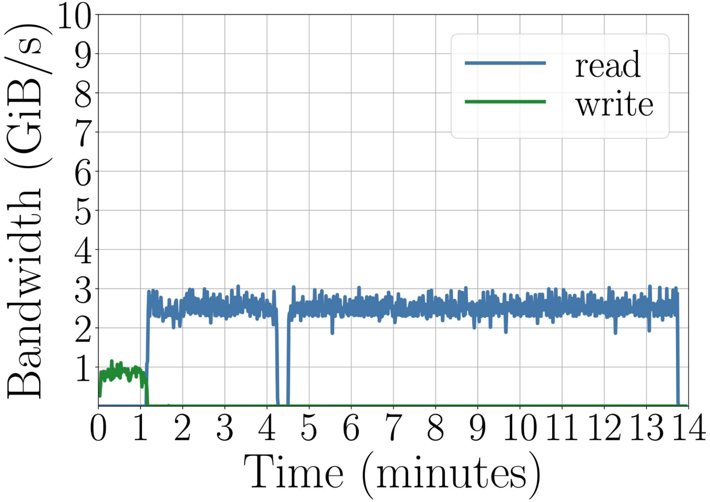
The SSD's sectors are uniformly accessed, indicating there is no hot spots.

Model offloading with FlexGen (OPT-30B)

Batch Size = 1



Batch Size = 16

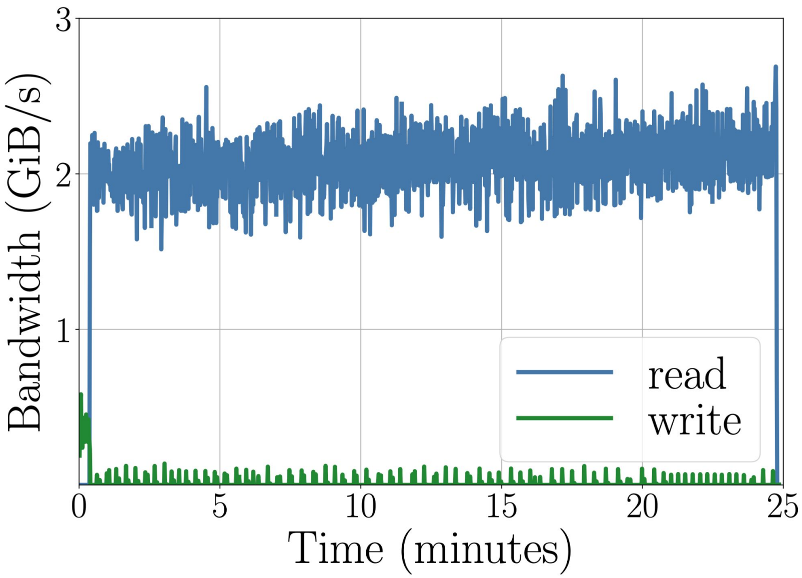


Similar I/O pattern between frameworks (DeepSpeed and FlexGen).

Neither DeepSpeed nor FlexGen can saturate the NVMeVirt SSD.

Q3: I/O access patterns of KV cache offloading.

KV Cache Offloading with FlexGen (OPT-6.7B, Batch Size 64)



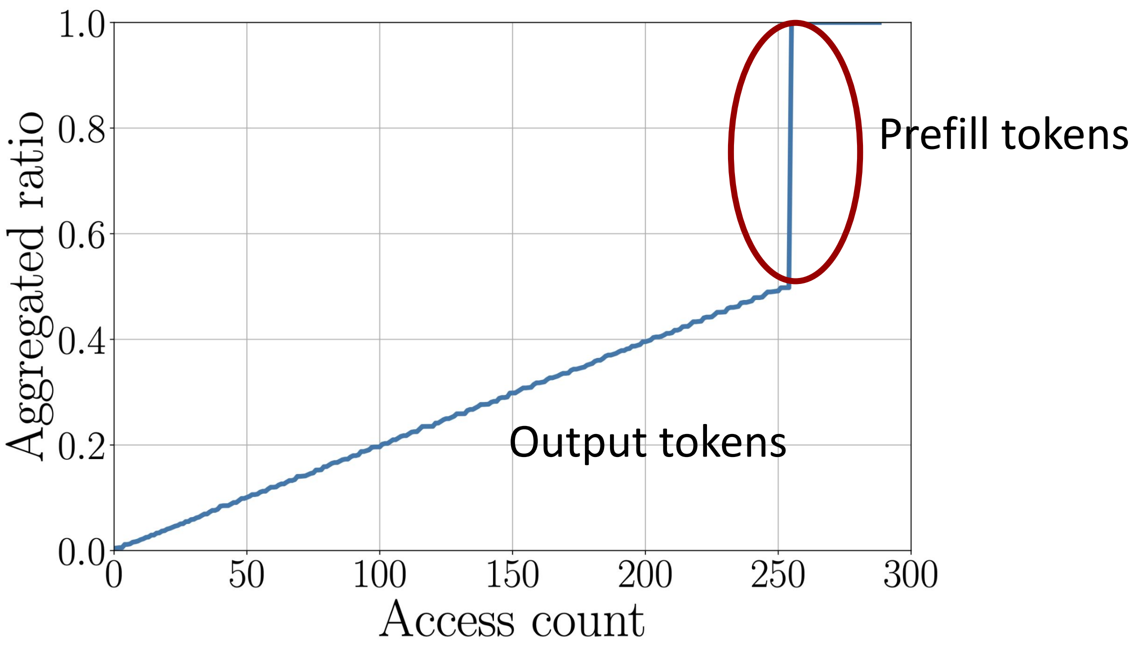
Average: 2.0 GiB/s.

Average: 11.0 MiB/s.

The read bandwidth of the KV cache is significantly higher than the write bandwidth.

The block-level I/O is dominated by 128 KiB reads and writes.

KV Cache Offloading with FlexGen (OPT-6.7B, Batch Size 64)



The sectors in KV cache offloading are accessed non-uniformly.

The earlier the KV cache is generated, the more times it is accessed.

Take-home Messages

1. Use libaio with tensor transferring for higher bandwidth.

- Use an I/O library optimized for deep learning for higher tensor transfer bandwidth.
- Use asynchronous I/O (such as libaio) than synchronous I/O interface.

2. LLM model offloading is dominated by large reads.

- Neither DeepSpeed nor FlexGen can reaches the maximum speed of the SSD.
- The I/O workload is dominated by 128 KiB reads.
- The sectors are accessed uniformly.

3. LLM KV cache offloading has higher read than write bandwidth.

- Read 2.0 GiB/s vs. write 11.0 MiB/s.
- Non-uniform I/O access.

GitHub

Paper: https://atlarge-research.com/pdfs/2025-cheops-llm.pdf
Source code:
https://github.com/stonet-research/cheops25-IO-characterization-of-LLM-model-kv-cache-offloading-nvme

PDF

Future Work

1. Effect of different hardware on the performance of SSD offloading during LLM inference.

- Different models and numbers of GPUs.
- Different models and numbers of SSDs.

2. LLM model-aware optimizations.

- Sparsity of activations.
- Different contributions of each tokens to the result.

3. Real-world LLM serving workloads.

- Multi-round conversations.

Resources

References

[1] DeepNVMe https://www.deepspeed.ai/tutorials/deepnvme/
[2] DeepSpeed https://github.com/deepspeedai/DeepSpeed
[3] FlexGen https://github.com/FMInference/FlexLLMGen
[4] HuggingFace: OPT model. https://huggingface.co/docs/transformers/en/model_doc/opt
[5] ZeRO-Inference: 20X Faster Inference Through Weight Quantization and KV Cache Offloading. https://github.com/microsoft/DeepSpeedExamples/blob/master/inference/huggingface/zero_inference/README.md
[6] Aminabadi et.al. DeepSpeed-Inference: Enabling Efficient Inference of Transformer Models at Unprecedented Scale. In SC22. https://doi.org/10.1109/SC41404.2022.00051
[7] Sheng et.al. FlexGen: High-Throughput Generative Inference of Large Language Models with a Single GPU. In ICML'23 https://proceedings.mlr.press/v202/sheng23a.html
[8] Kim et.al. NVMeVirt: A Versatile Software-defined Virtual NVMe Device. In FAST'23.

Further Reading

[1] Chitty-Venkata et.al. A Survey of Techniques for Optimizing Transformer Inference. J. Syst. Archit. 144 (2023), 102990. https://doi.org/10.1016/J.SYSARC.2023.102990
[2] Gao et.al. Cost-efficient Large Language Model Serving for Multi-turn Conversations with CachedAttention. In ATC'24.
[3] Lee et.al. InfiniGen: Efficient Generative Inference of Large Language Models with Dynamic KV Cache Management. In OSDI'24

Thank you!
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Questions?

Paper: https://atlarge-research.com/pdfs/2025-cheops-llm.pdf
Source code:
https://github.com/stonet-research/cheops25-IO-characterization-of-LLM-model-kv-cache-offloading-nvme

Backup Slides

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This work: LLM offloading to SSD during inference.