PIM Is All You Need: A CXL-Enabled GPU-Free System for Large Language Model Inference

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* Equal Contribution

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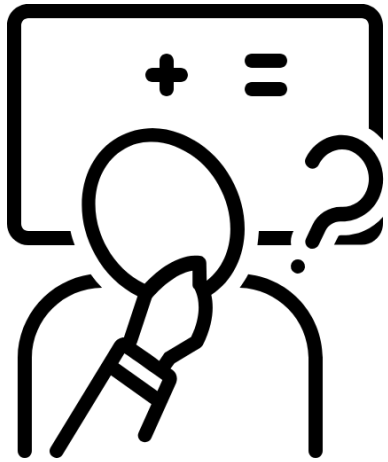
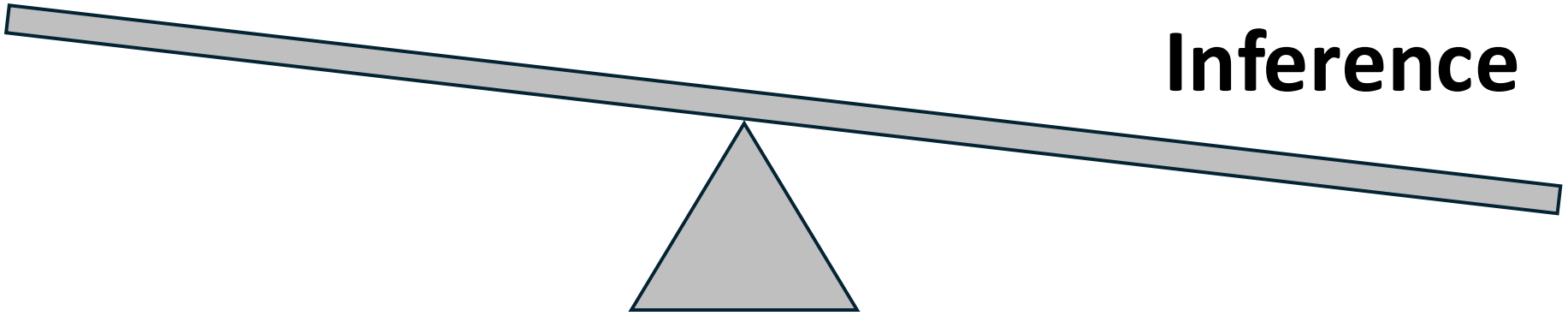
Open-source: https://github.com/Yufeng98/CENT


Training

2x
Carbon
Footprint

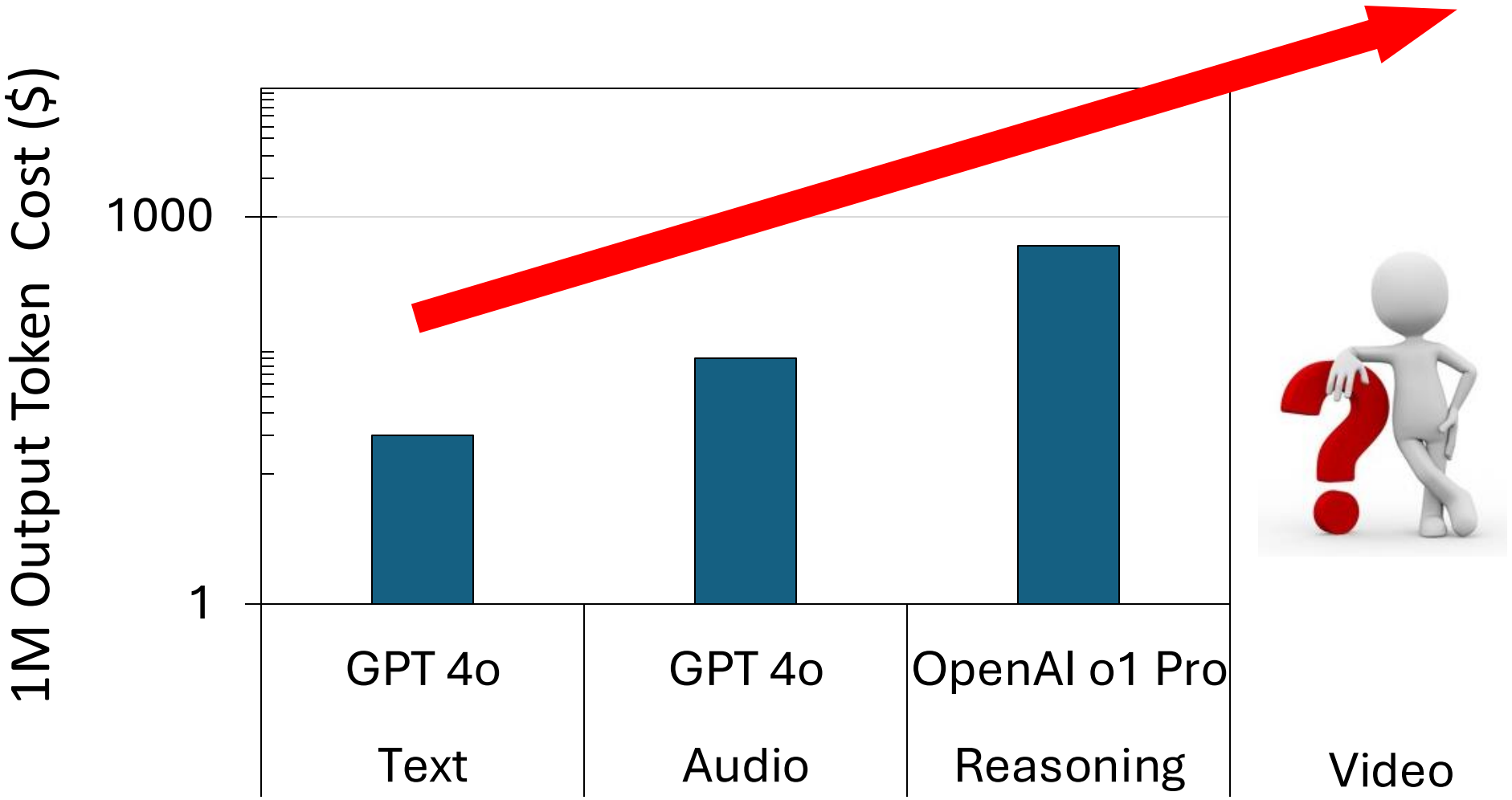


Inference



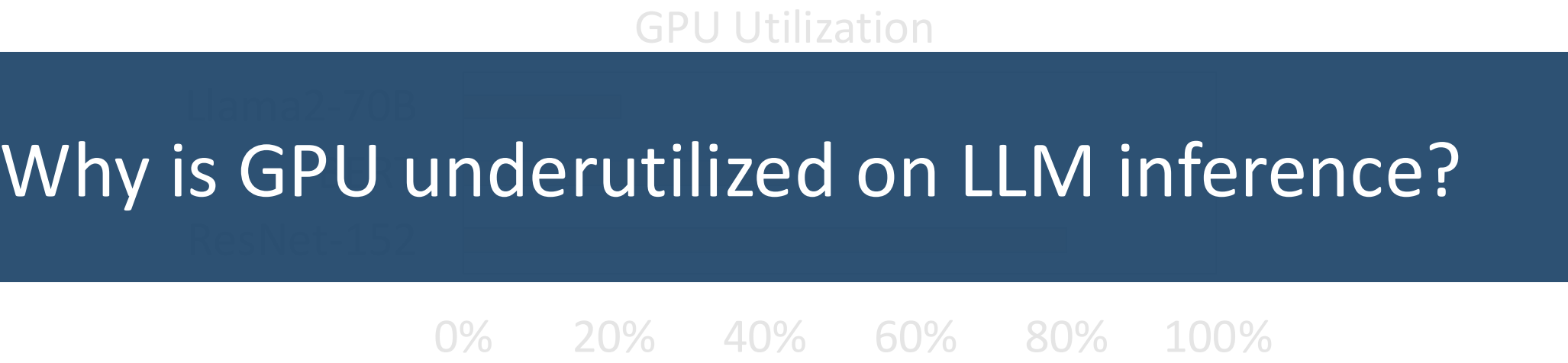
[1] Meta AI, Sustainable AI: Environmental Implications, Challenges and Opportunities, MLSys'22

LLM Inference Cost Is Increasing



[1] https://openai.com/api/pricing/

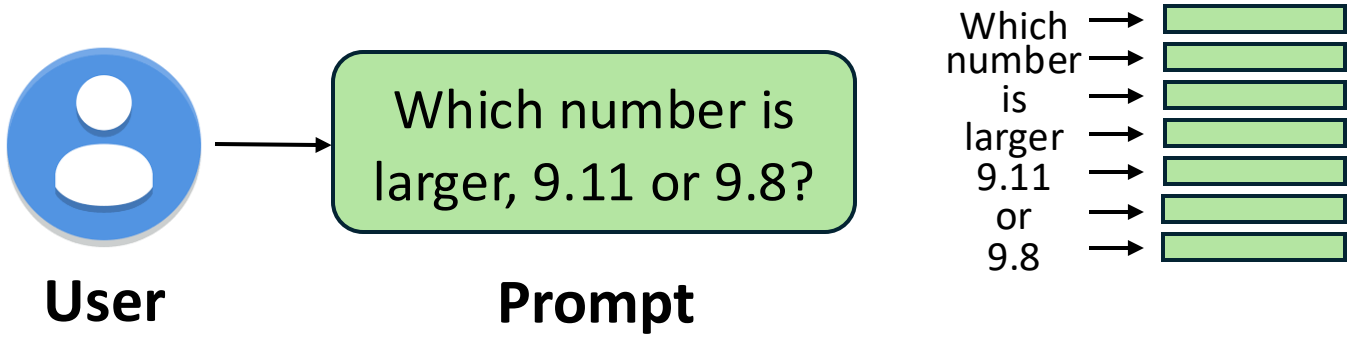
Expensive GPU Server Is under Low Utilization

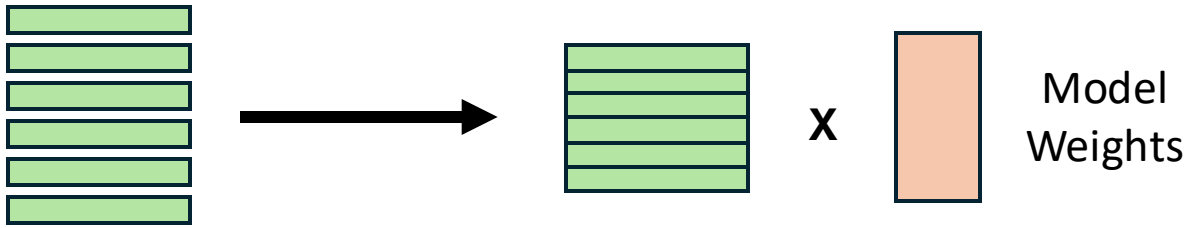


Why is GPU underutilized on LLM inference?

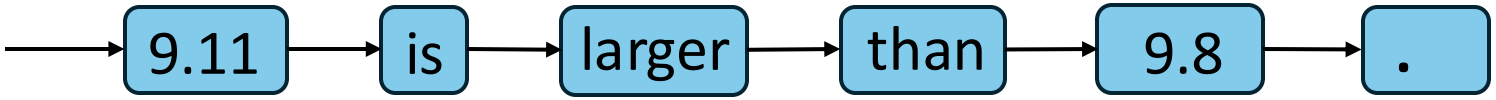
How does LLM Inference work?

Prefill Stage
(Prompt Summarization)

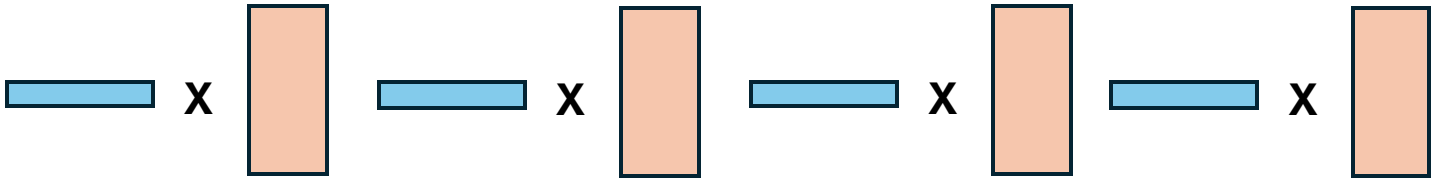




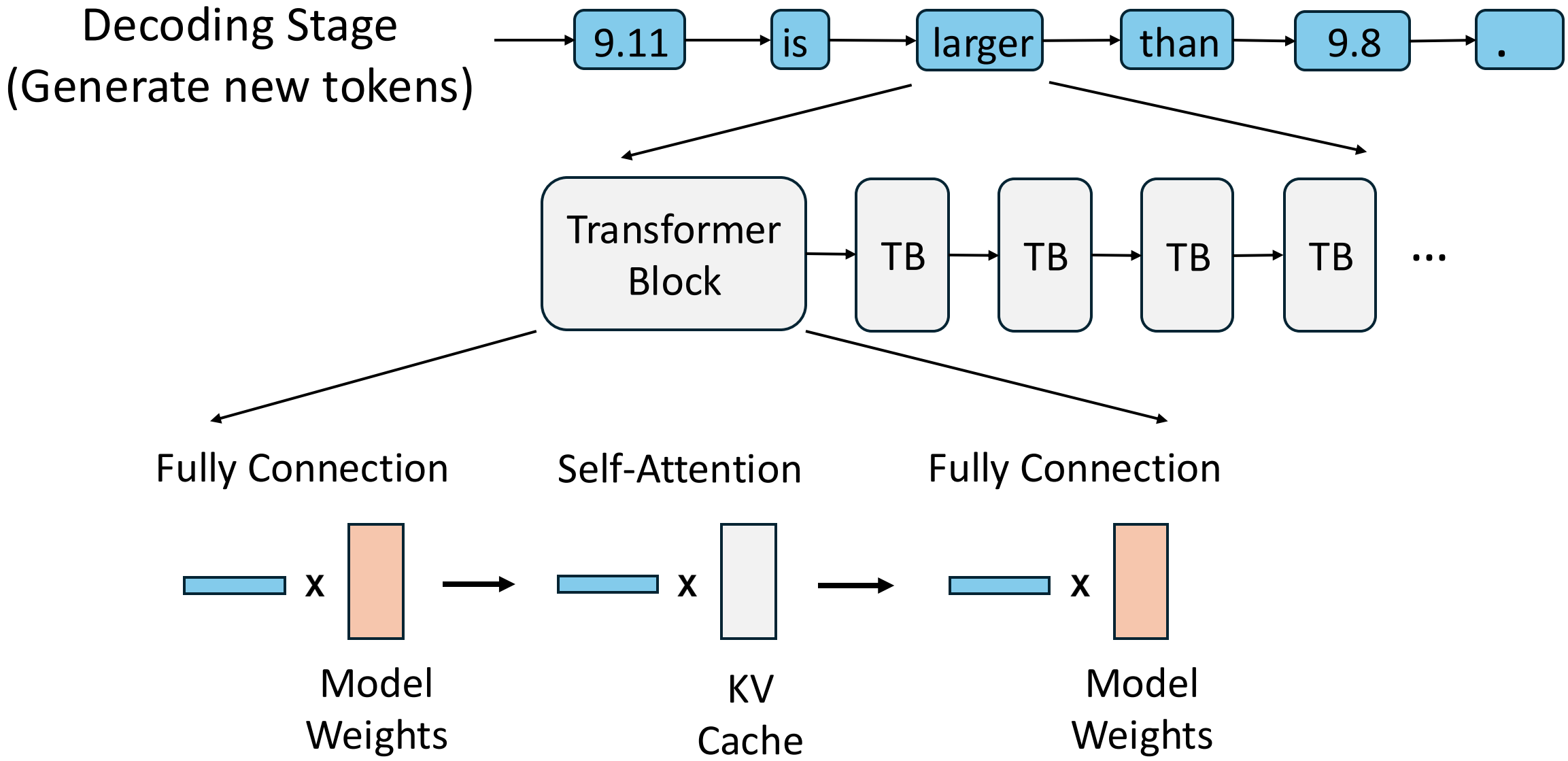
Decoding Stage
(Generate new tokens)



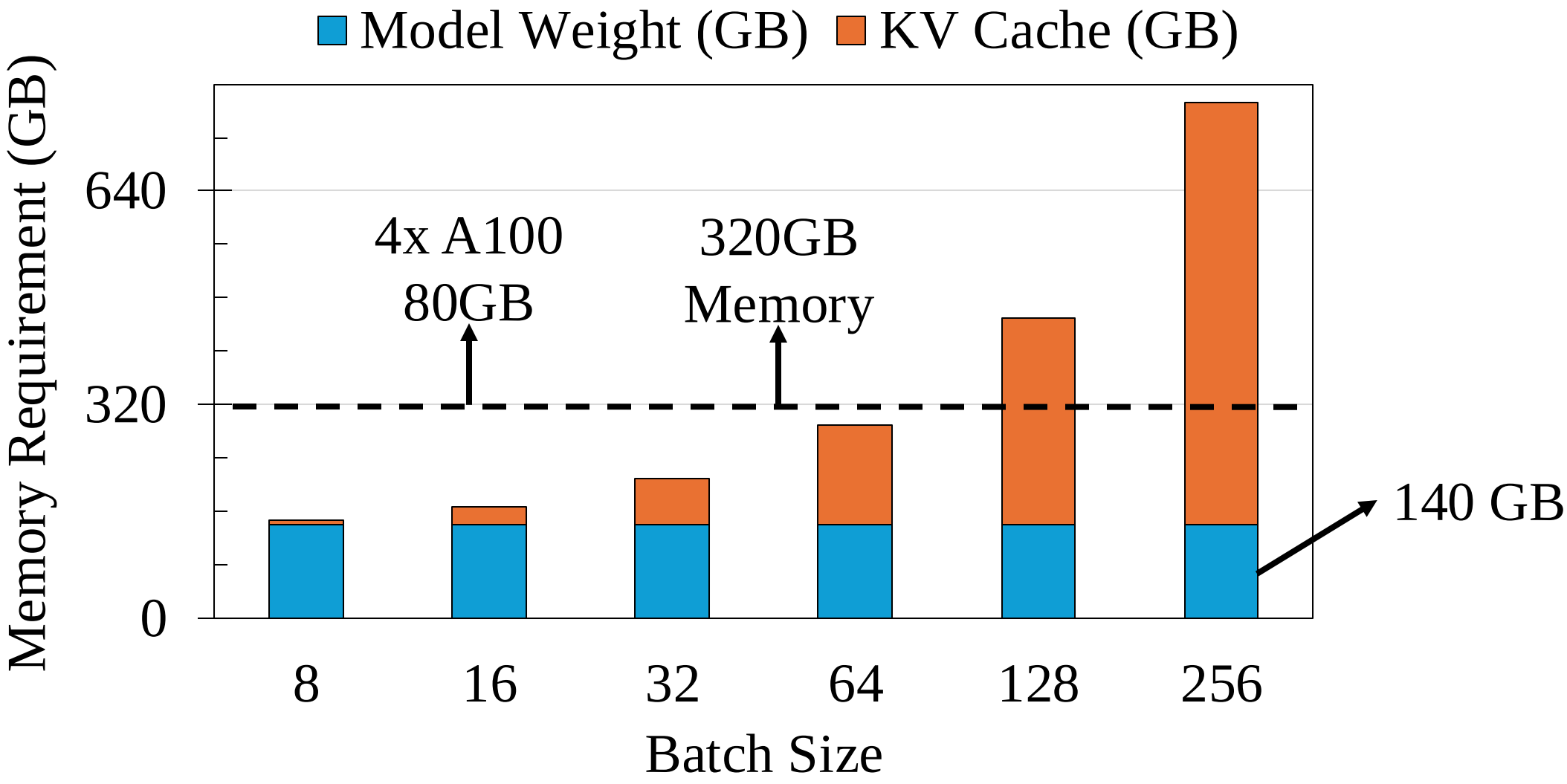
Generate output tokens



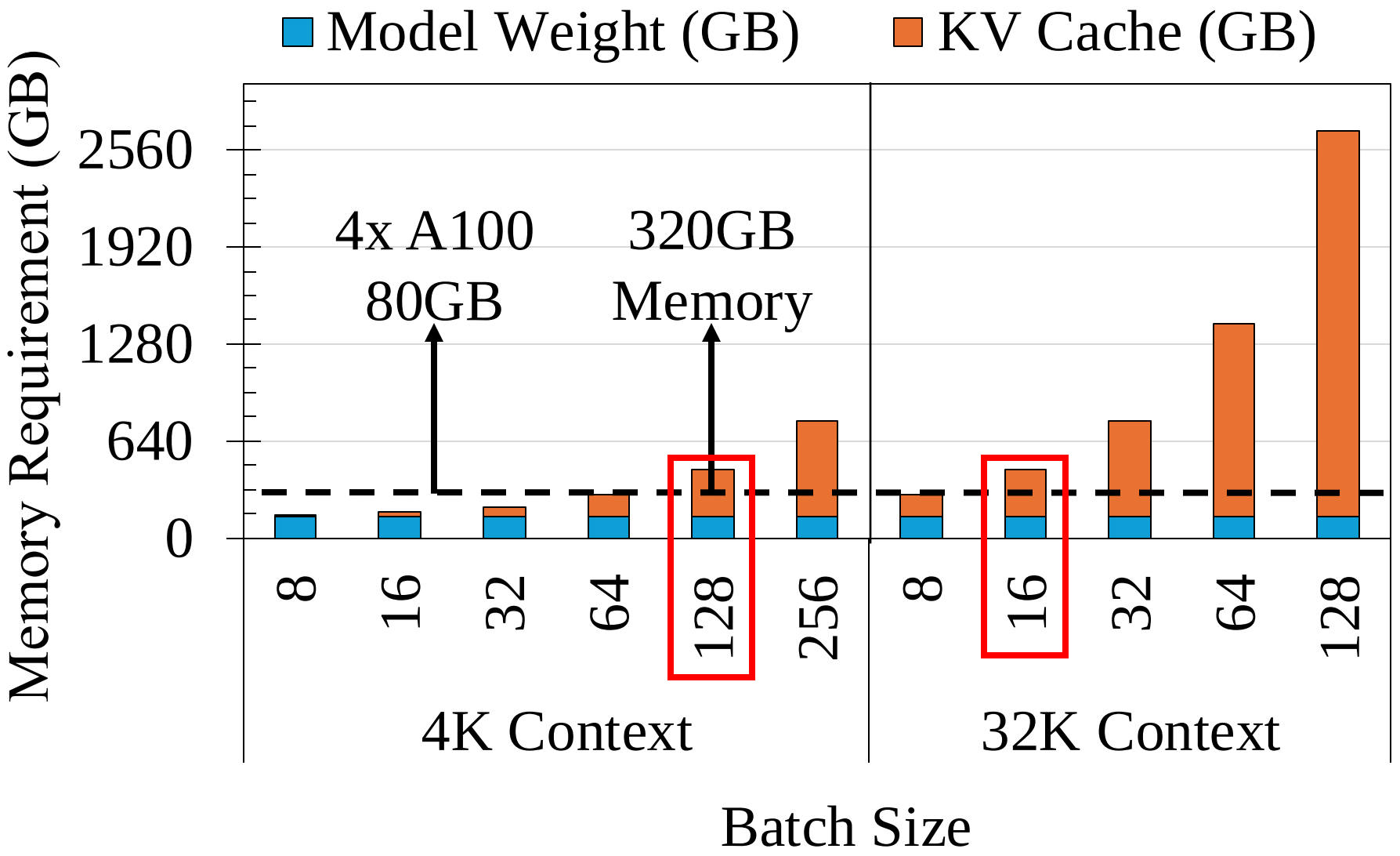
LLM Inference Decoding



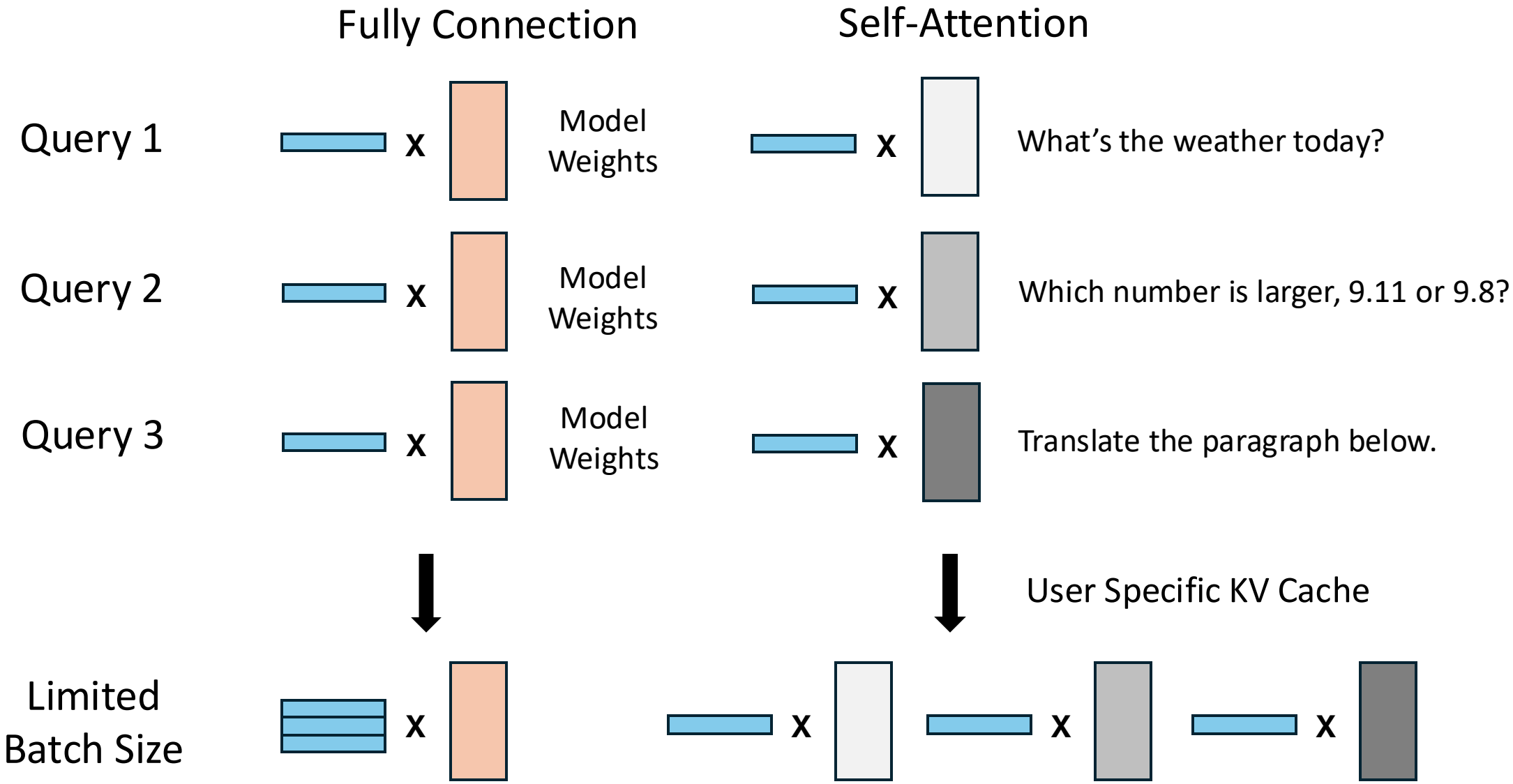
Llama 70B Inference Memory Requirement



GPU Memory Capacity Limits LLM Inference Batch Size

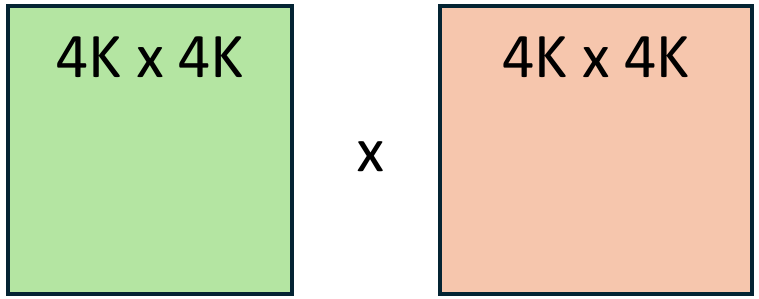


Batch Queries in Decoding



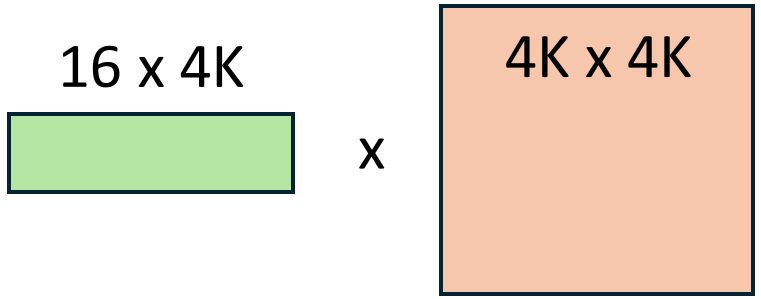
LLM Inference Has Low Operational Intensity

GEMM



Operational Intensity = **2000** Ops/Byte

LLM Inference



Operational Intensity = **16** Ops/Byte

A100 GPU Operational Intensity = **156** Ops/Byte

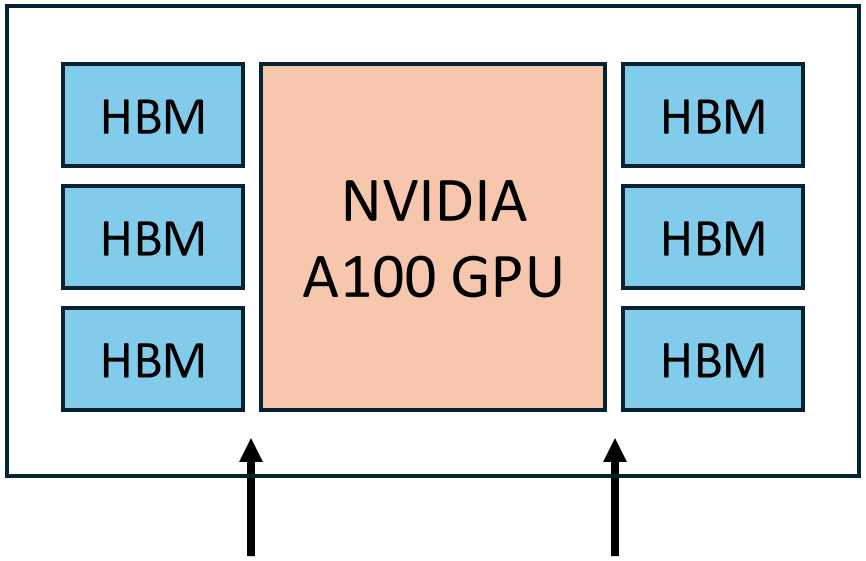
H100 GPU Operational Intensity = **295** Ops/Byte

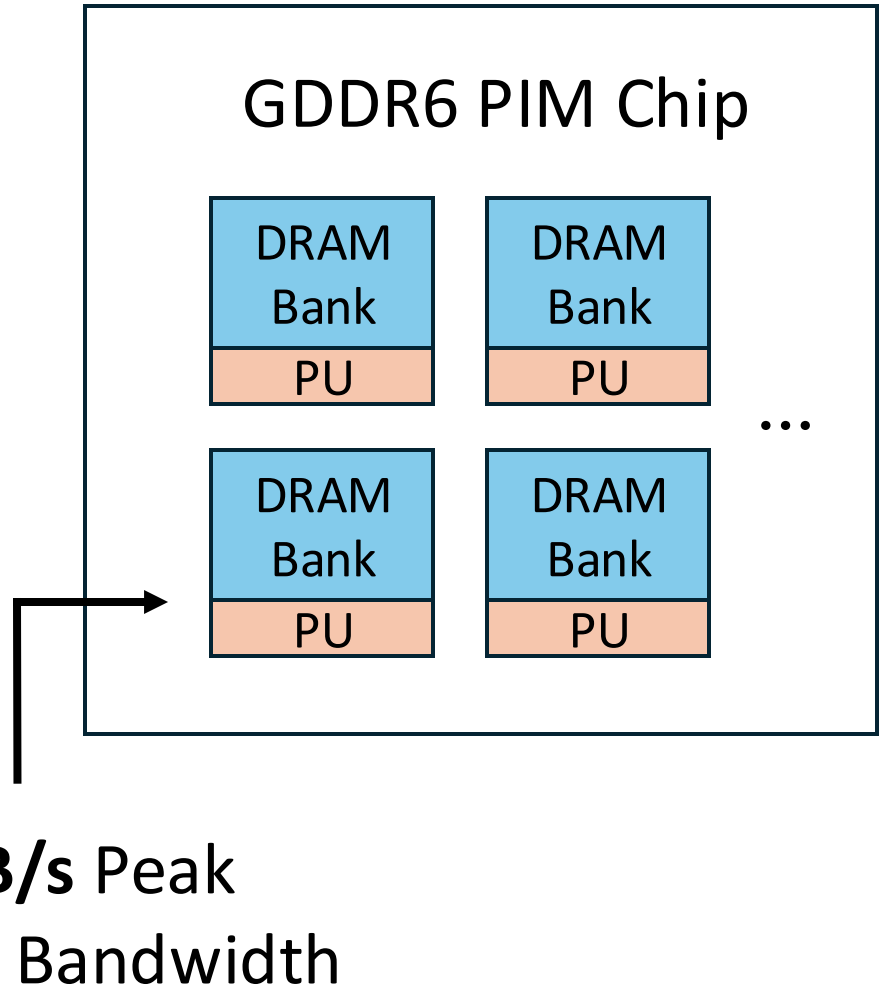
LLM Inference Has Low Operational Intensity

How can we efficiently serve LLM Inference with **Low Operational Intensity**

$$\text{Operational Intensity} = \frac{\text{Compute Throughput}}{\text{Memory Bandwidth}}$$

PIM Provides High Memory Bandwidth





LLM Inference Requires Large Memory Capacity

Llama 70B
4K Context
Batch = 128

450 GB

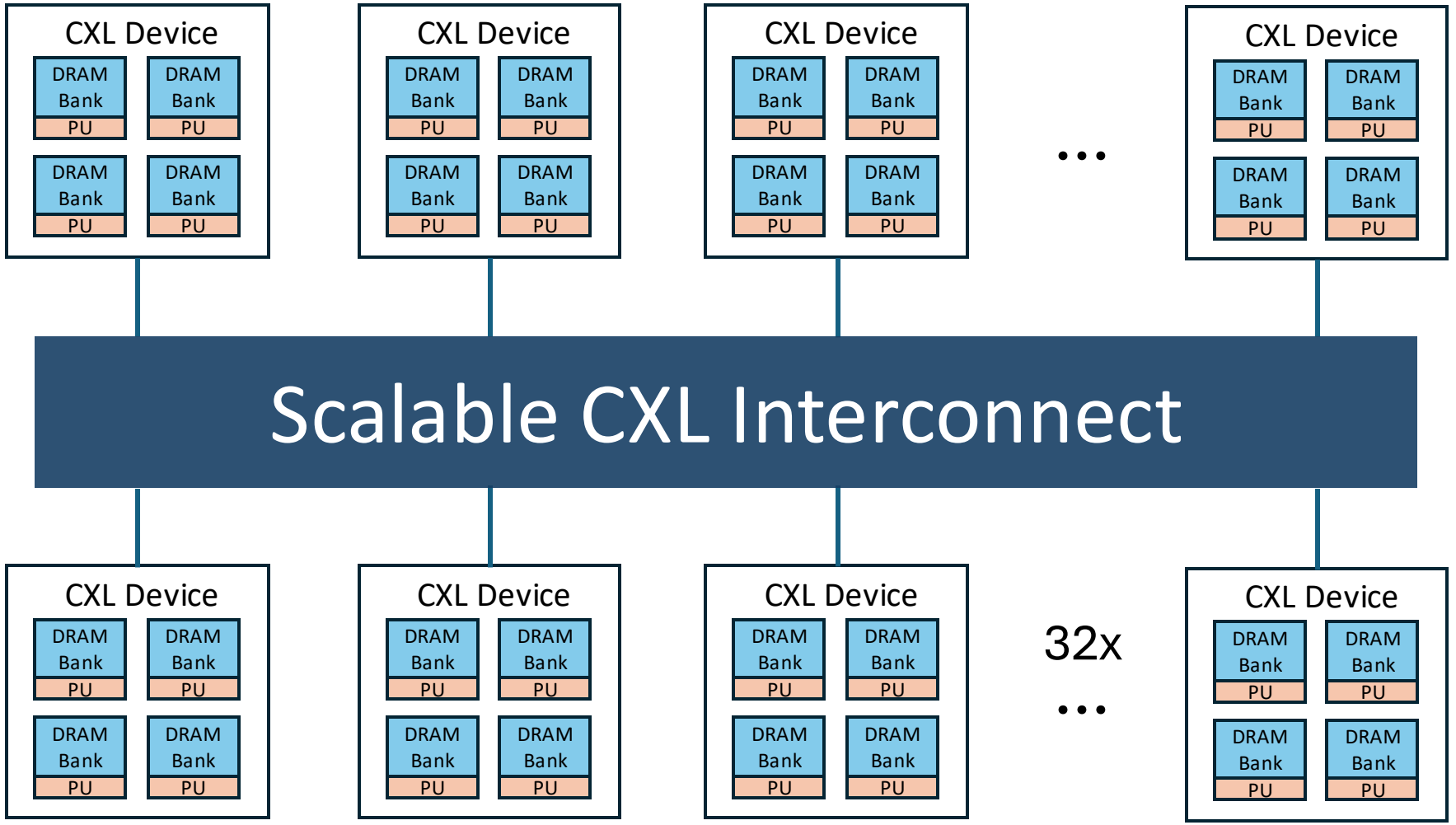
140 GB
Model Weights

310 GB
KV Cache

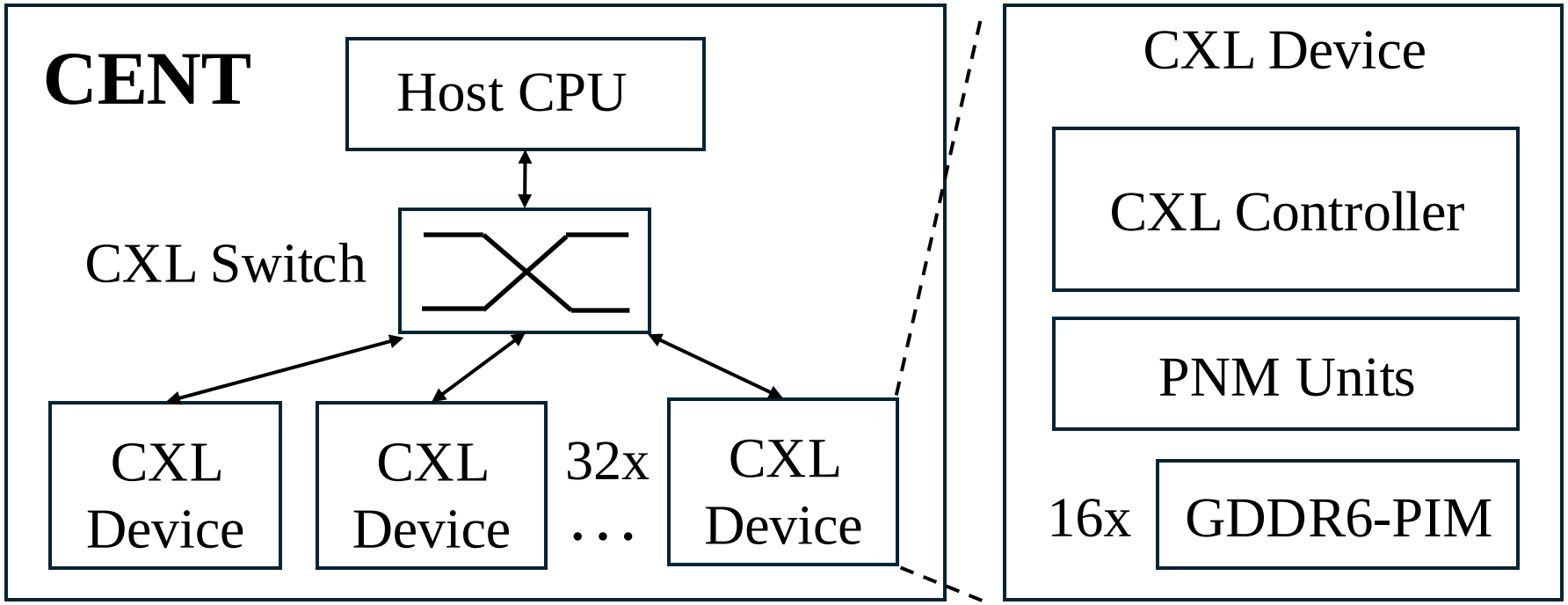
	Llama2	Llama3	DeepSeek R1	OpenAI o1	Gemini 1.5 Pro	Grok-3	Claude 3.5
Model	70 B	405 B	671 B	-	-	-	-
Contexts	4K	128 K	128 K	200 K	2 M	1 M	200 K

https://platform.openai.com/docs/models#o1, https://developers.googleblog.com/en/new-features-for-the-gemini-api-and-google-ai-studio/, https://x.ai/blog/grok-3, https://docs.anthropic.com/en/docs/about-claude/models, The Llama 3 Herd of Models, DeepSeek-R1: Incentivizing Reasoning Capability in LLMs via Reinforcement Learning

CXL Interconnect Provides Substantial Memory Capacity



CENT Architecture



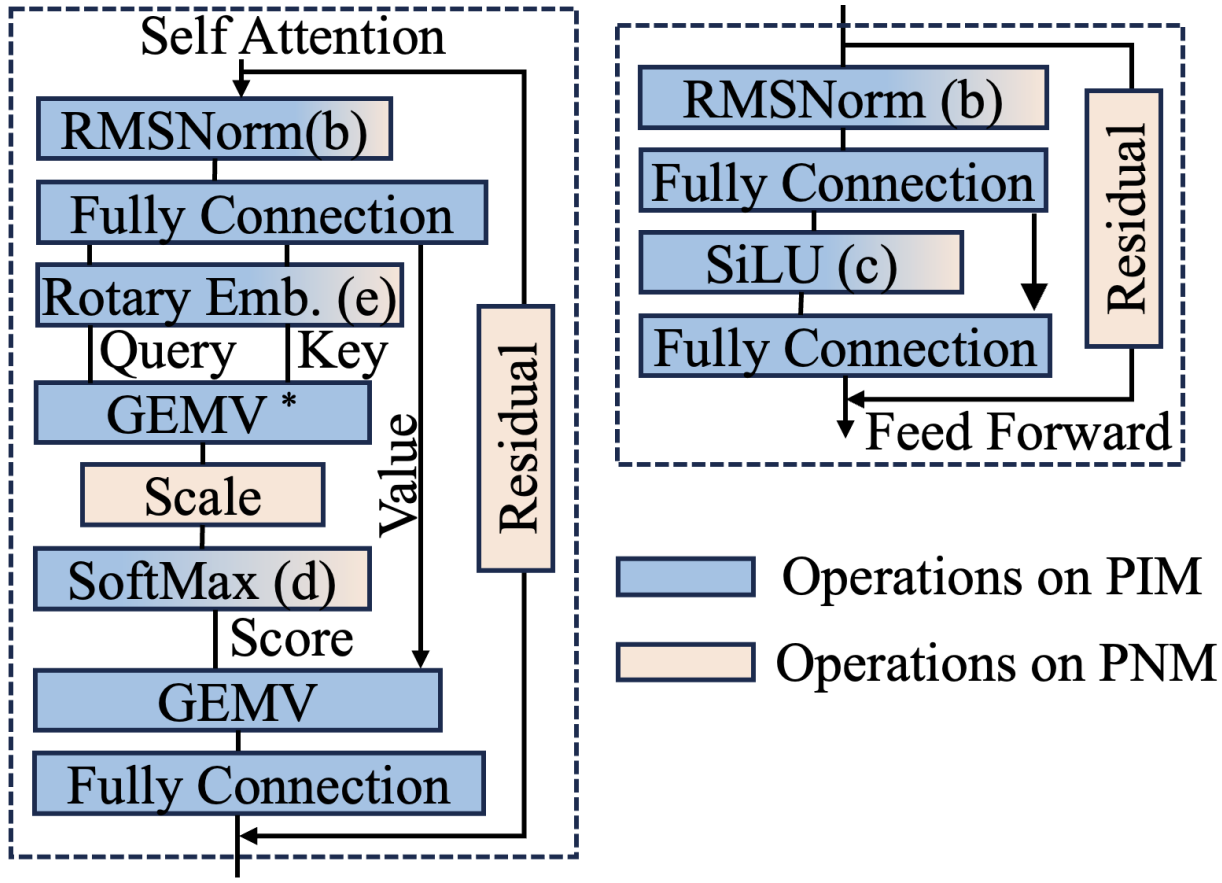
Full Transformer Block Execution on the CXL Device

PIM Module **99%**

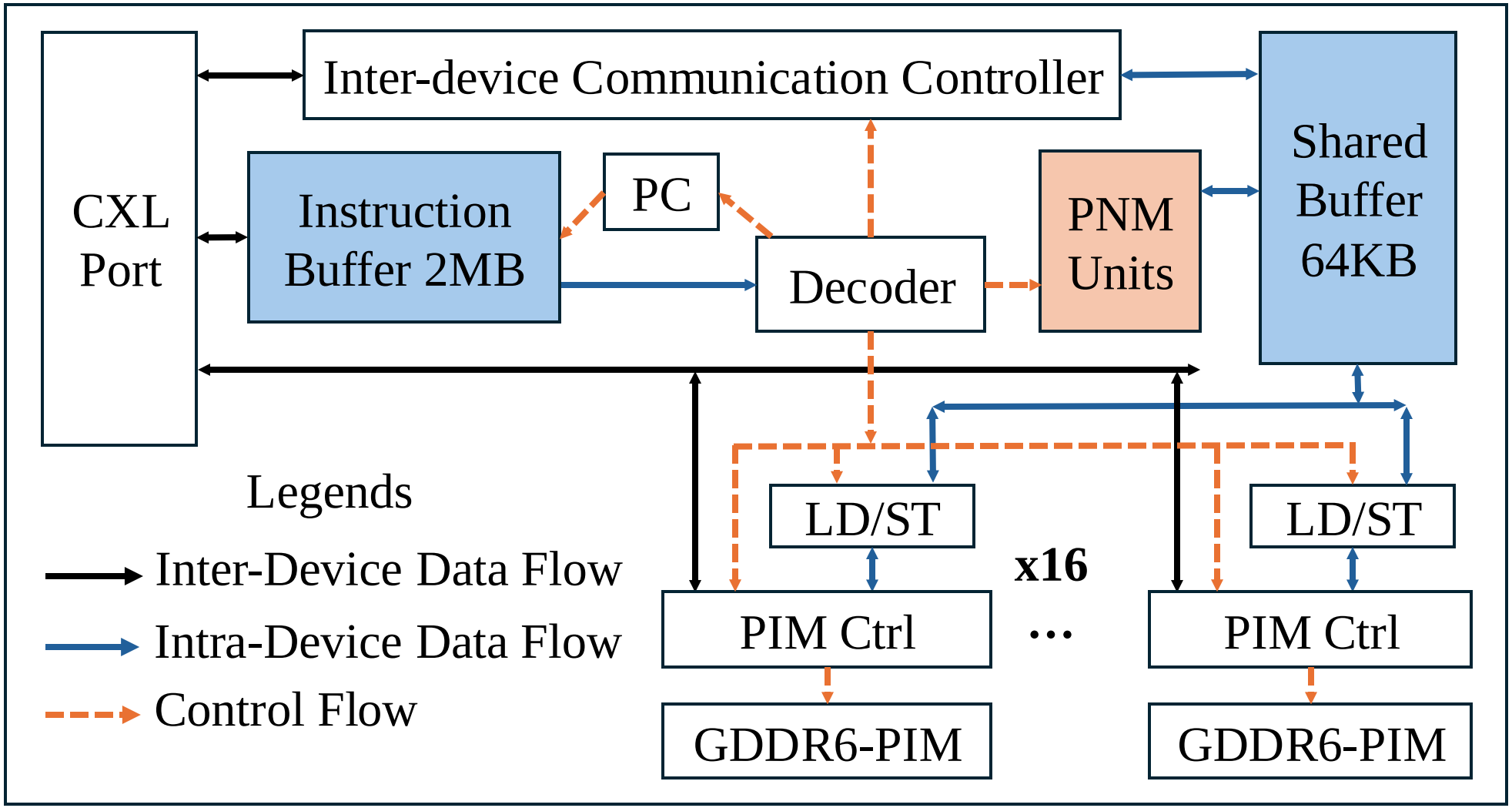
- Vector Multiplication
- Element-wise Multiplication

PNM Accelerator

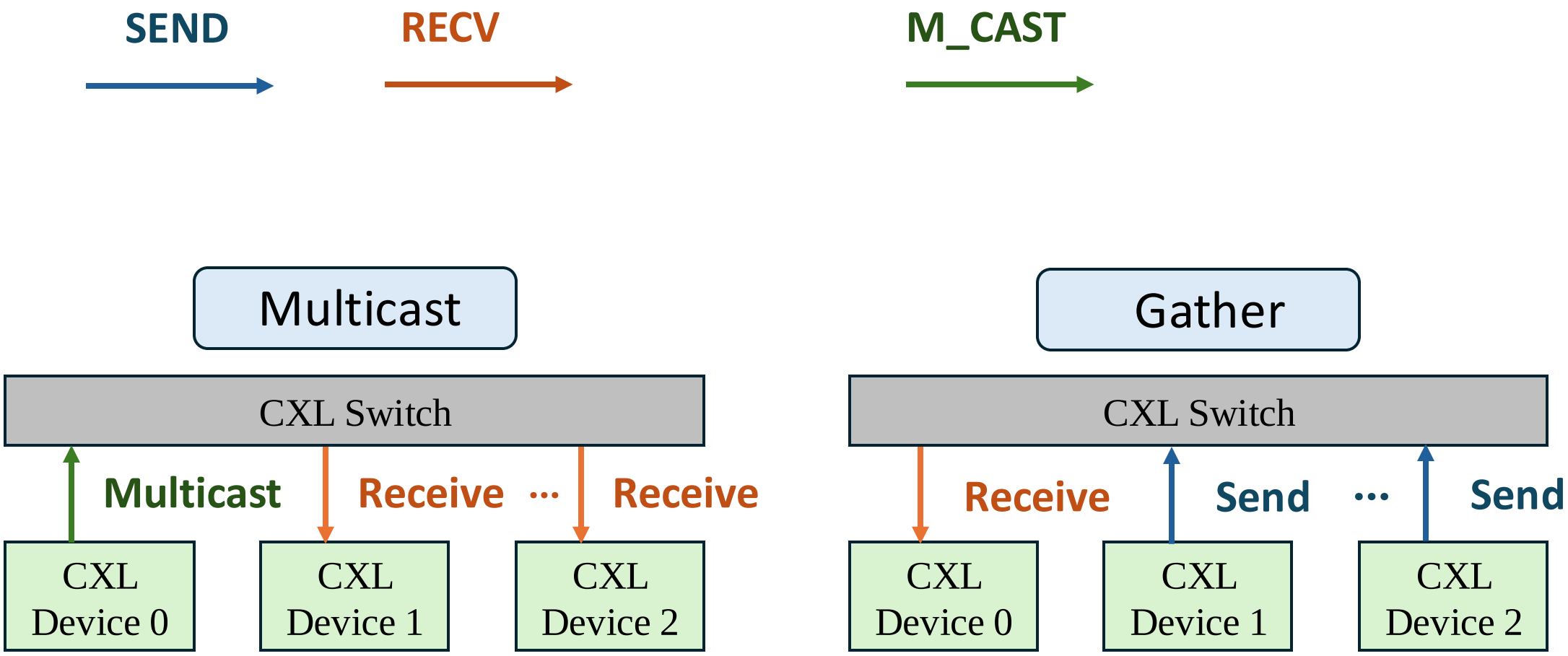
- Vector Addition Units
- Reduction Trees
- Exponent Processors
- RISC-V cores for Special Functions



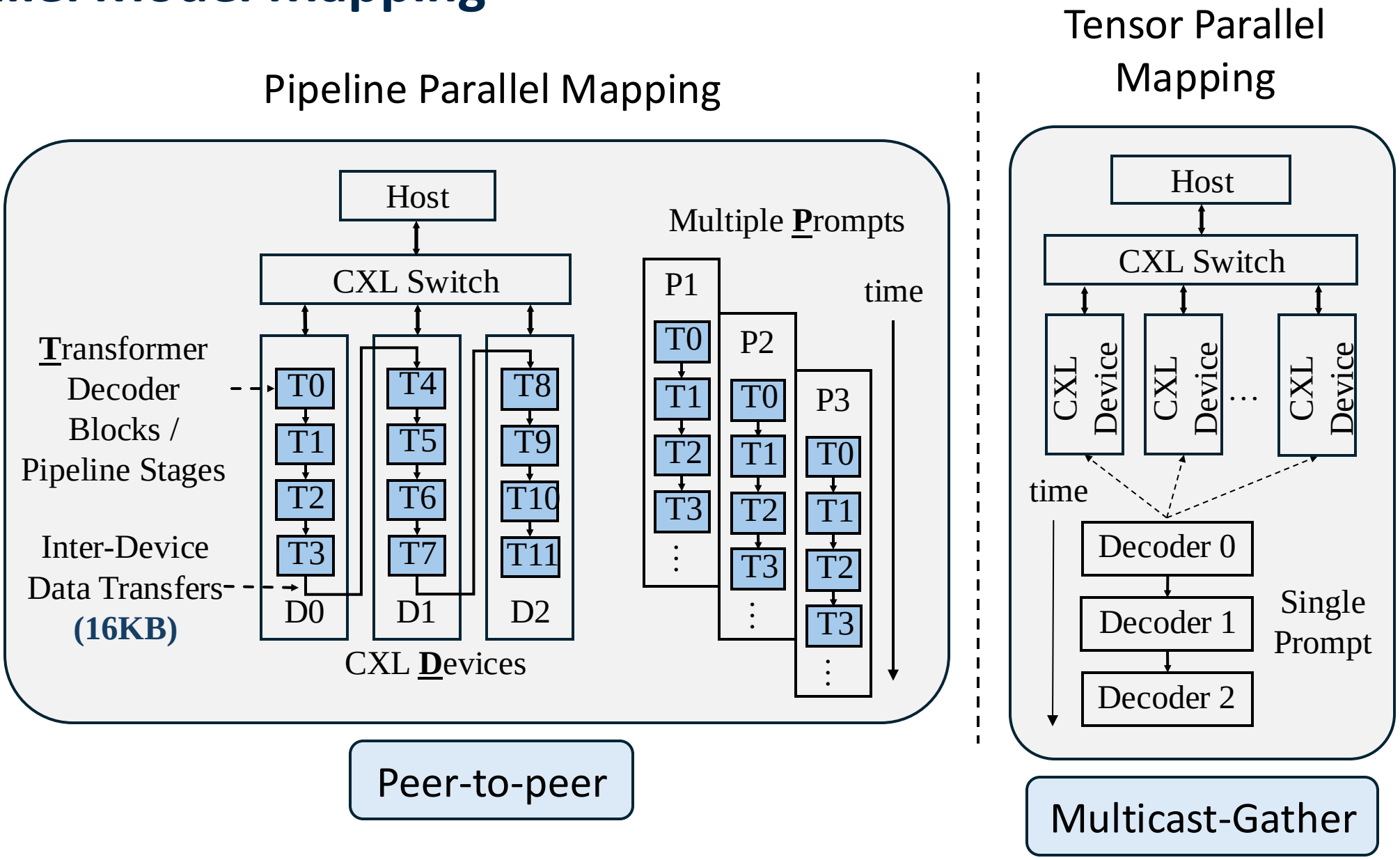
CXL Device Architecture



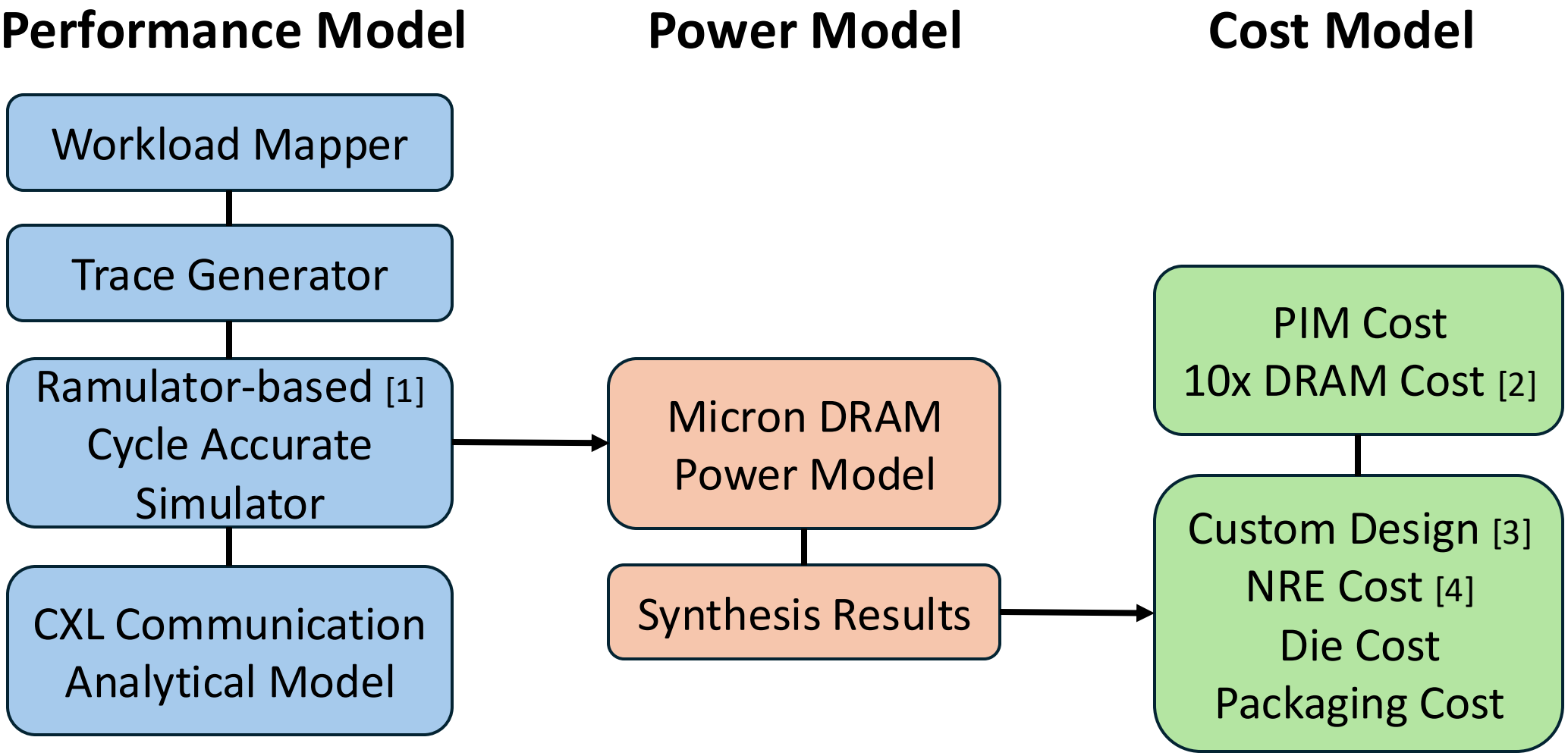
Inter-Device CXL Communication



Parallel Model Mapping



Evaluation Methodology



[1] Ramulator 2.0: A Modern, Modular, and Extensible DRAM Simulator.
[2] UPMEM. Accelerating compute by cramming it into dram memory
[3] Supply chain aware computer architecture. In Proceedings of the 50th Annual International Symposium on Computer Architecture, pages 1–15, 2023.
[4] Moonwalk: Nre optimization in ASIC clouds. ACM SIGARCH Computer Architecture News, 45(1):511–526, 2017

CENT versus GPU Baseline

System	CENT	GPU
Hardware	32 CXL Devices	4 NVIDIA A100
Memory	512 GB, GDDR6	320 GB, HBM2E

CENT versus GPU Baseline

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Compute Throughput	608 TFLOPS	1248 TFLOPS

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Compute Throughput	608 TFLOPS	1248 TFLOPS
Peak Bandwidth	**512 TB/s**	**8 TB/s**
3-Year *Owned* Total Cost of Ownership	0.73 $/hour	1.76 $/hour
3-Year *Rental* Total Cost of Ownership	1.05 $/hour	5.45 $/hour

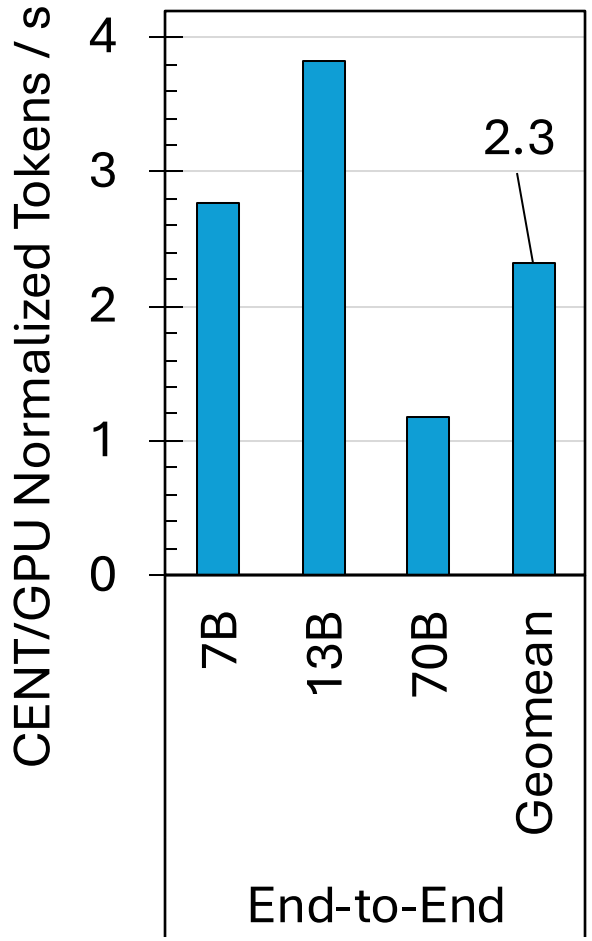
2.4x 

Cost Efficiency Comparison

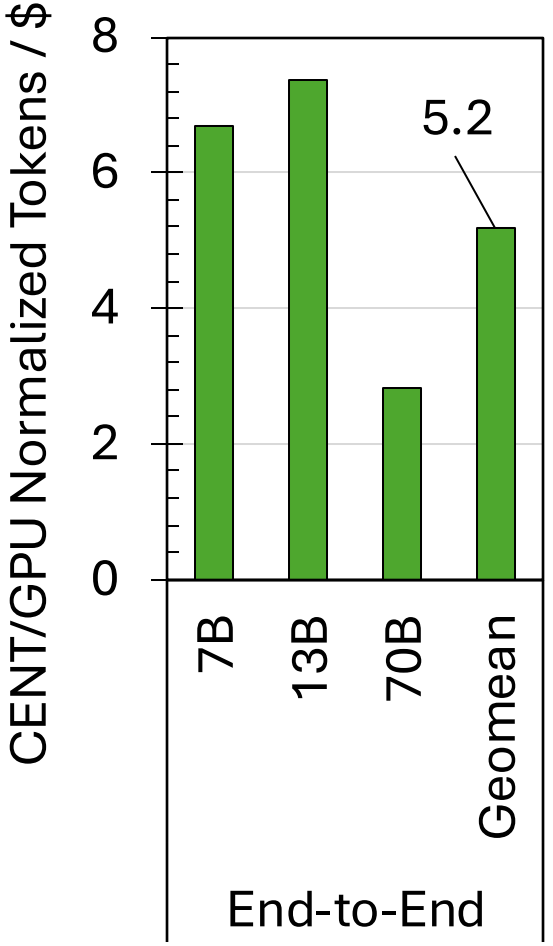
Prefill Tokens = 512
Decoding Tokens = 3.5K

	3-Year Owned TCO
GPU	1.76 $/hour
CENT	0.73 $/hour

2.4x
Hardware Cost

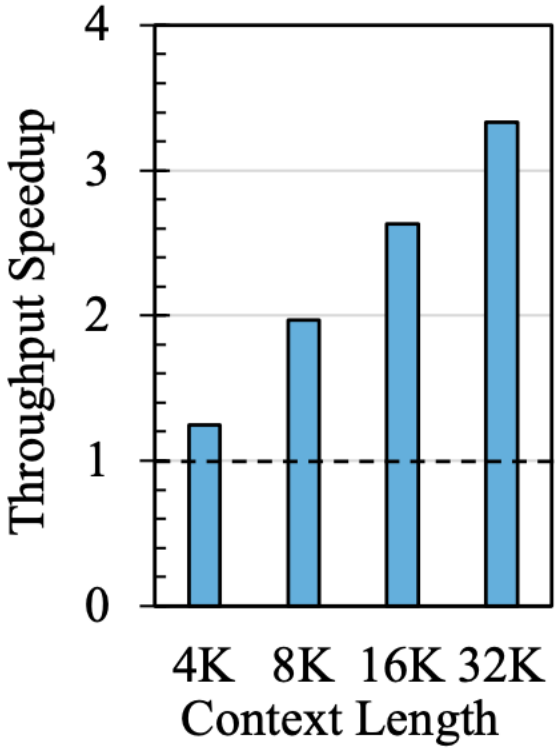


2.3x
Throughput

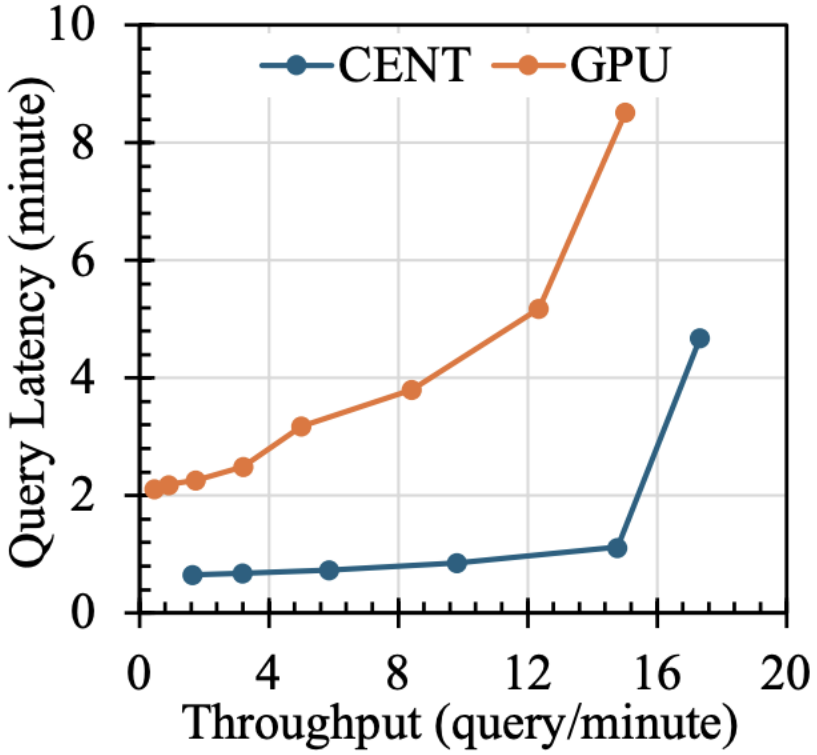


5.2x
Tokens per $

Long Context and QoS Analysis

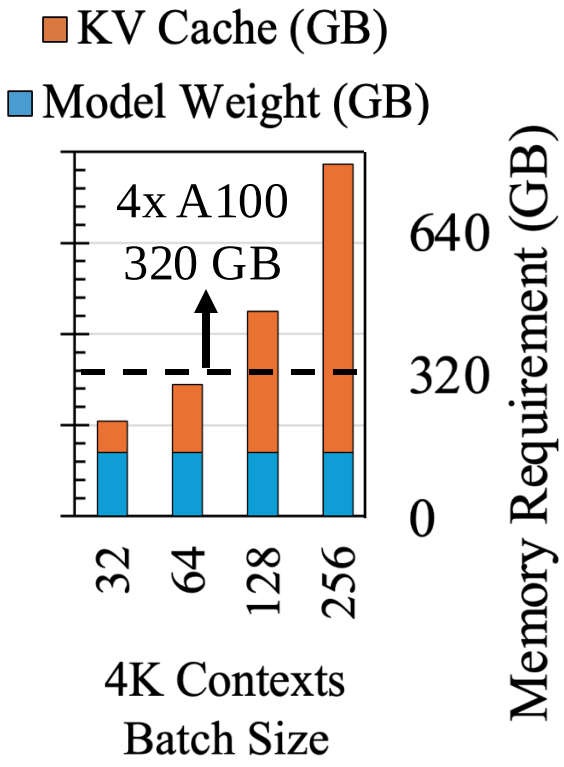


Decoding Throughput



Comparison at 4K Context

CENT: A CXL-Enabled PIM System



Limited Batch

Sequential self-attention execution

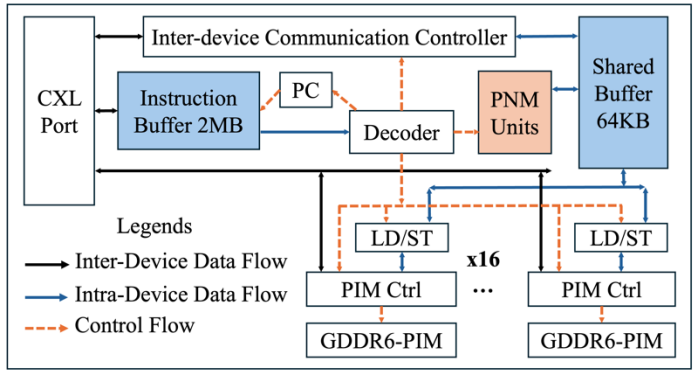
Low GPU Utilization

Low Operational Intensity

16 TB/s per GDDR6 channel

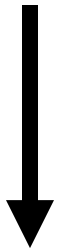
DRAM Bank

PU



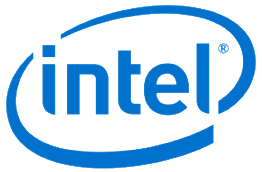
CENT: A CXL-Enabled PIM System

2.4x
Hardware Cost



2.3x
Throughput

5.2x
Tokens per $



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CENT Paper

CENT Artifact