Oaken: Fast and Efficient LLM Serving with Online-Offline Hybrid KV Cache Quantization

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LLM Serving at Scale

- LLM serving system should simultaneously handle **a large number of, long-context requests**

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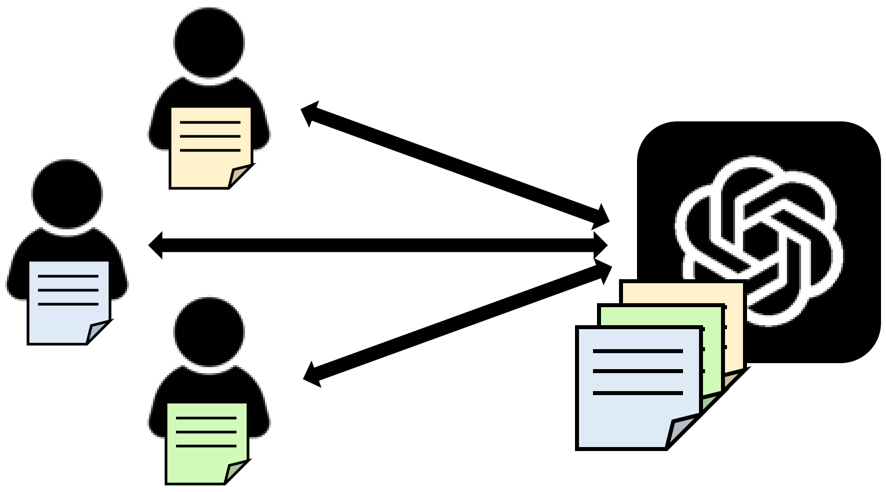
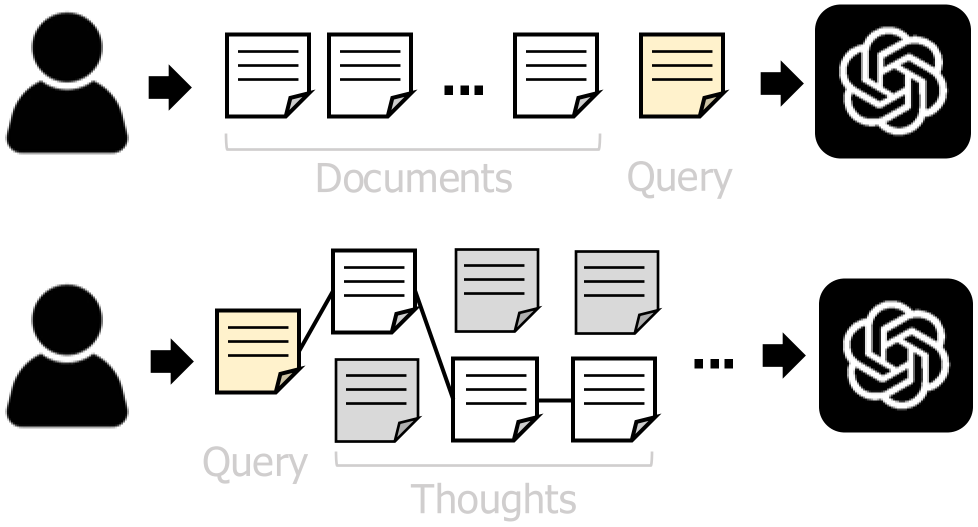
Large Batch Size



LLM serving system batches multiple requests (+10,000) from users

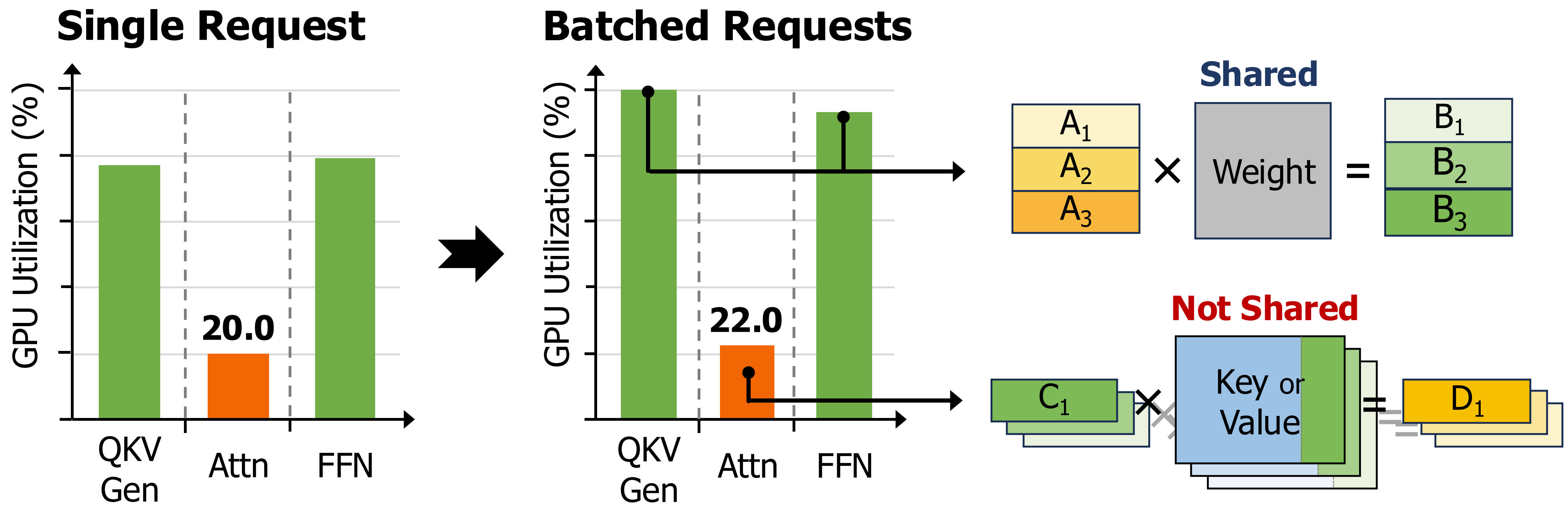
Long Context Length



Recent LLM tasks *(e.g., RAG, reasoning)* involve over tens of thousands of tokens

Larger Batch & Longer Context put pressure on Memory Capacity & Bandwidth

KV Cache Matters for "Bandwidth"

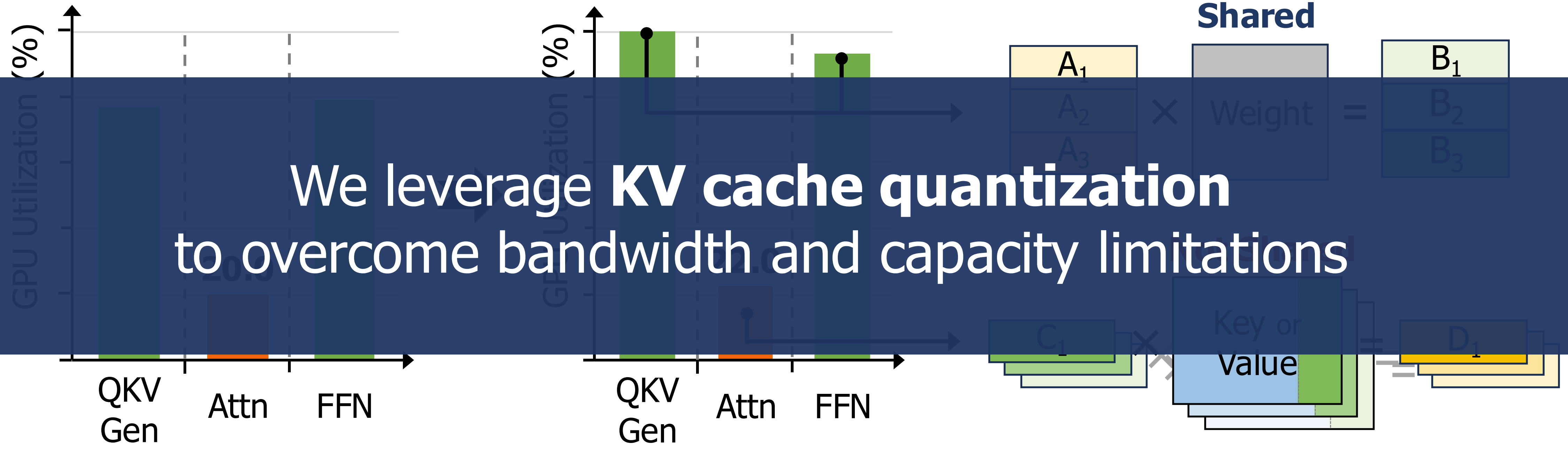


** NVIDIA A100, Llama2-13B, context length: 1K*

- Increasing batch size improves utilization **except for attention operation**
- Attention operation is **bandwidth-bound** due to un-sharable KV cache

KV Cache Matters for "Bandwidth"

Single Request **Batched Requests**



We leverage **KV cache quantization**
to overcome bandwidth and capacity limitations

** NVIDIA A100, Llama2-13B, context length: 1K*

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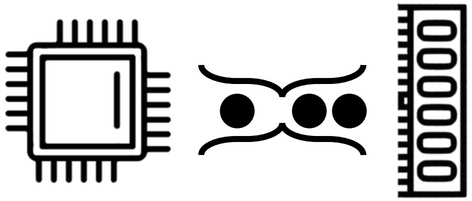
- Attention operation is **bandwidth-bound** due to un-sharable KV cache

Oaken achieves both high performance & accuracy through co-designing quantization algorithm & hardware modules

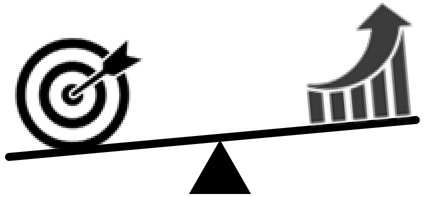
Overview of Oaken

Design Objectives

① Address memory bottleneck in LLM serving



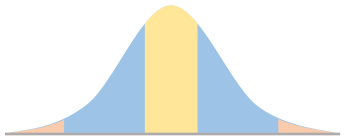
② Find sweet spot between accuracy & performance



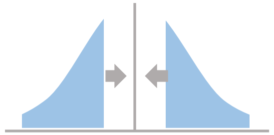
③ Maximize hardware utilization & performance

Algorithm Design

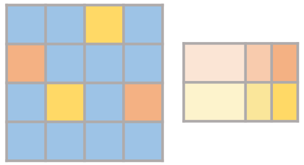
Threshold-based hybrid grouping



Group shift quantization

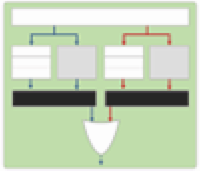


Dense-and-sparse encoding

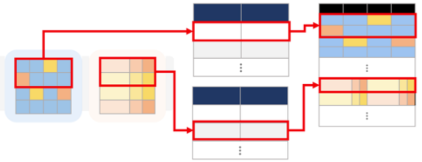


Hardware Design

Streamlined module architecture



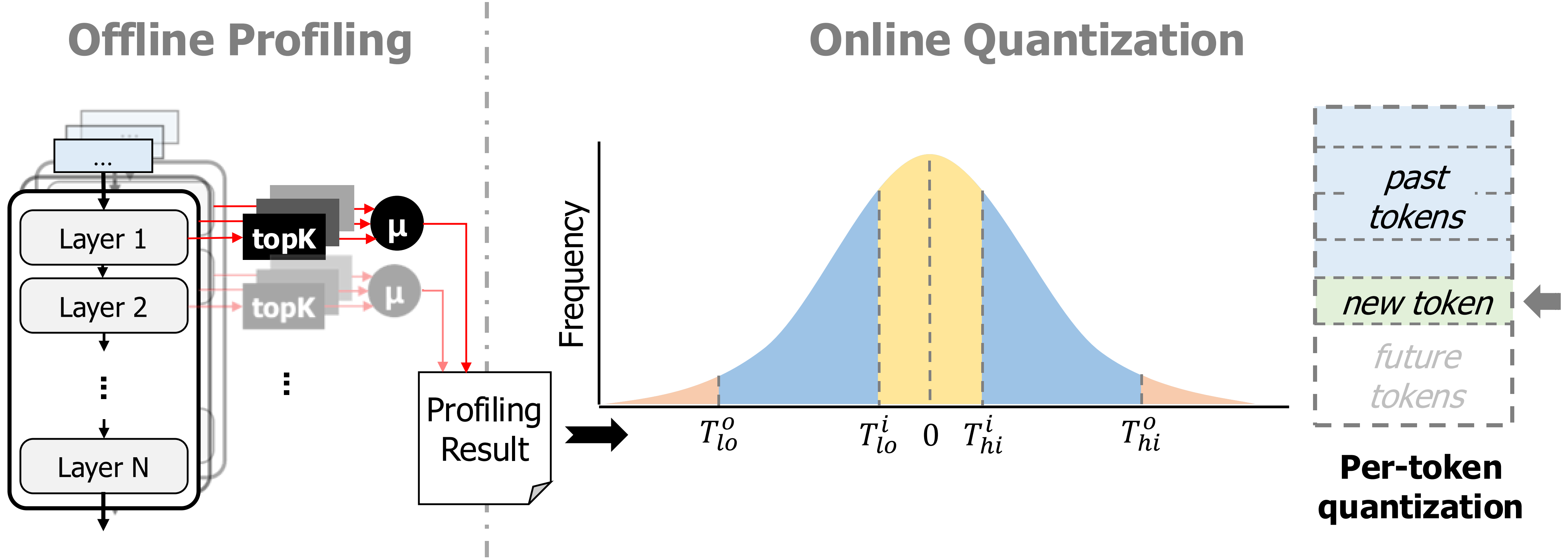
Page-based memory management



Key Observations on KV Distribution

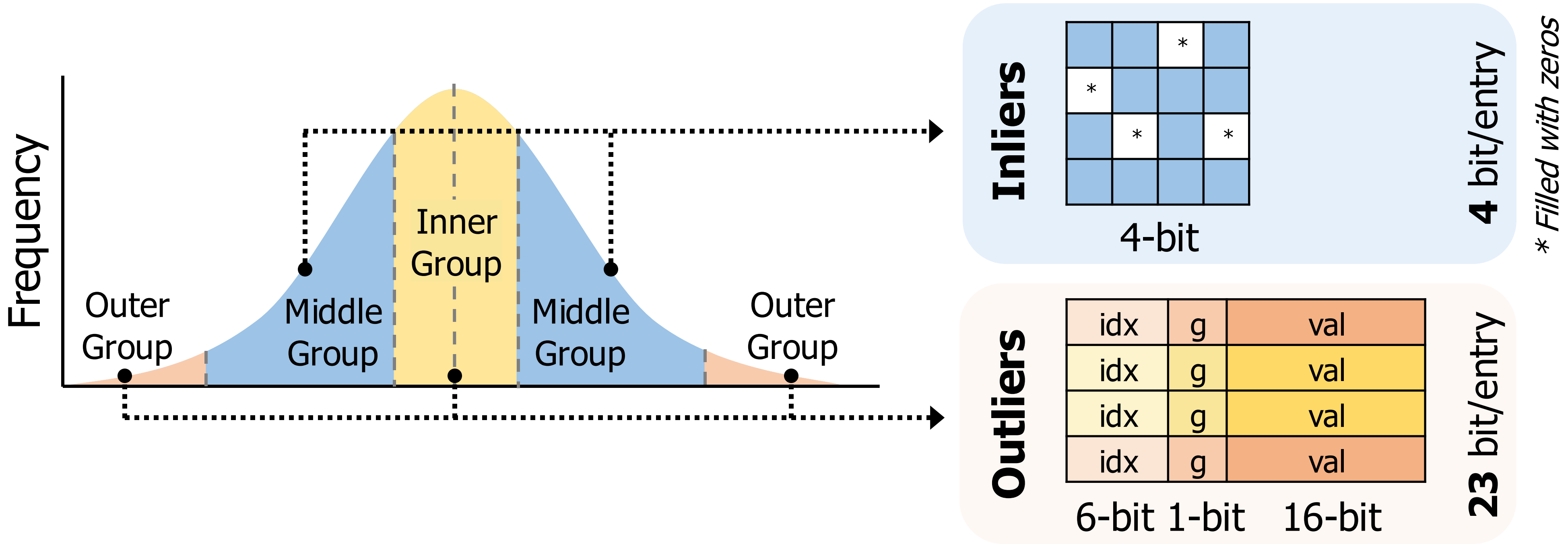
Observation		Insight
Observation 1 KV distribution **varies** across models and decoder layers	➡	**Insight 1** Oaken should determine quantization scale **for each model and decoder layer**
Observation 2 KV distribution is **consistent** across input datasets	➡	**Insight 2** Oaken can use shared quantization scale **regardless of model inputs**
Observation 3 KV distribution has **exceptions** to channel-wise pattern	➡	**Insight 3** Oaken should use **multiple quantization groups** segmented by magnitude

Threshold-based Online-Offline Quantization



- Offline profiling requires **one-time cost** for each model *(~100 inferences, ~10 min)*

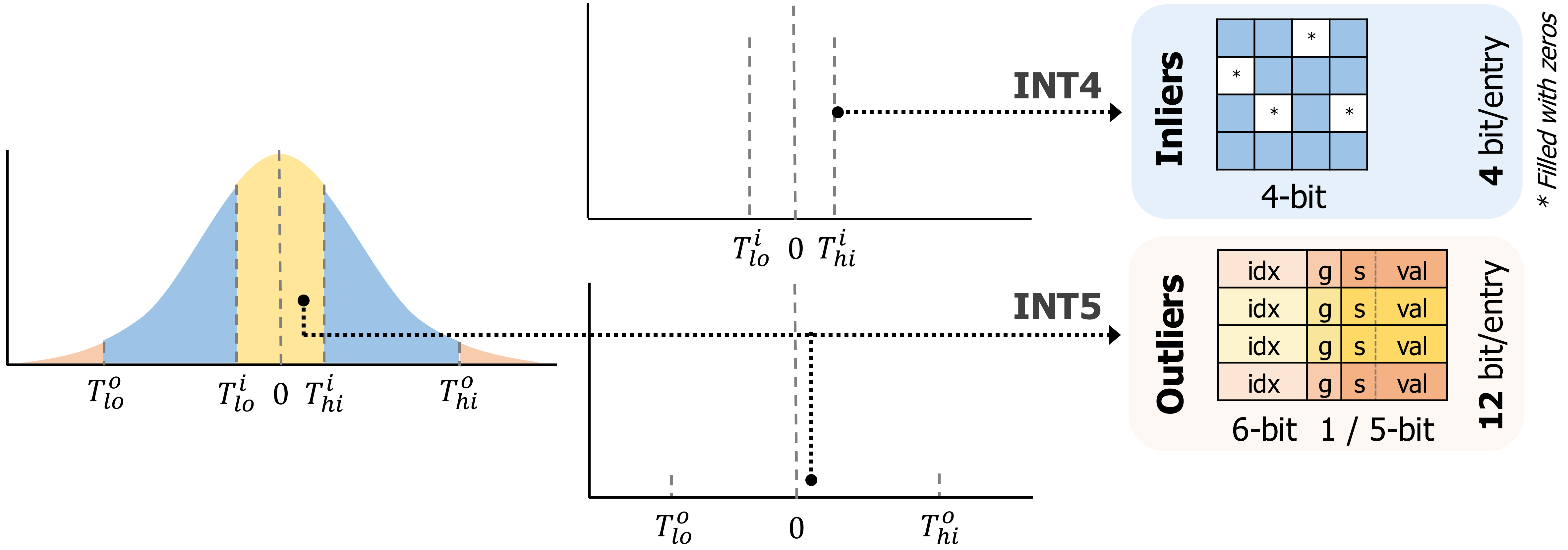
Threshold-based Online-Offline Quantization



Challenges:

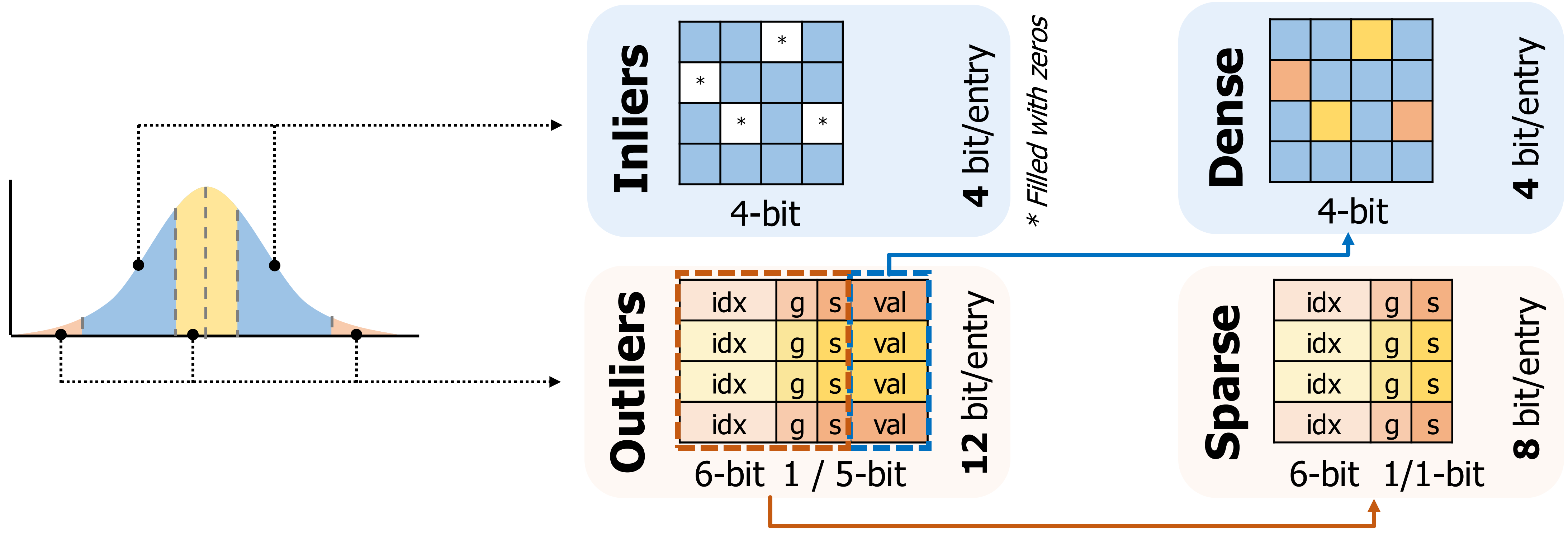
- Outliers add **storage and hardware costs**
- Outliers are **hard to quantize** due to large magnitude

Group Shift Quantization



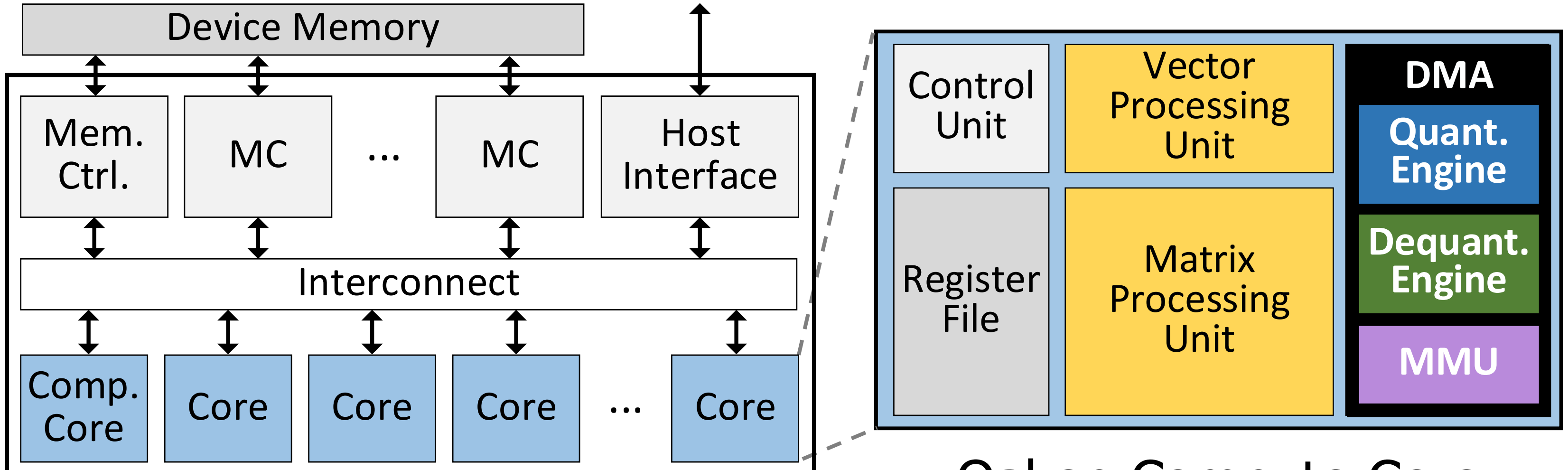
- **Group shift algorithm** reduces average bitwidth **from 5.9 to 4.8** ** 10% Sparsity*

Fused Dense-and-Sparse Encoding



- 8-bit sparse matrices are **hardware-efficient** and **memory-aligned**
- **Fused encoding** reduces average bitwidth **from 4.8 to 4.4** ** 10% Sparsity*

Oaken Accelerator Integration



Oaken Accelerator

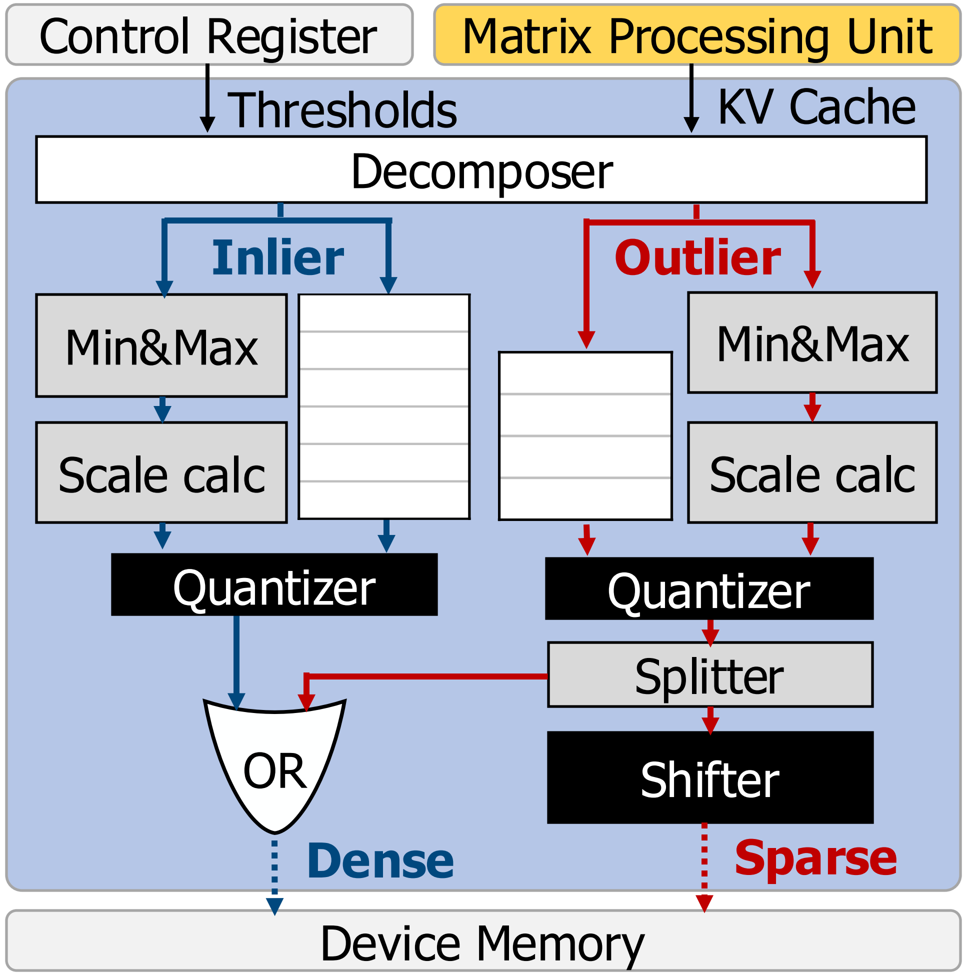
Oaken Compute Core

Module	Area
VPU	22.86%
MPU	6.03%
Quant. Engine	1.86%
Dequant. Engine	6.35%
Total	100%

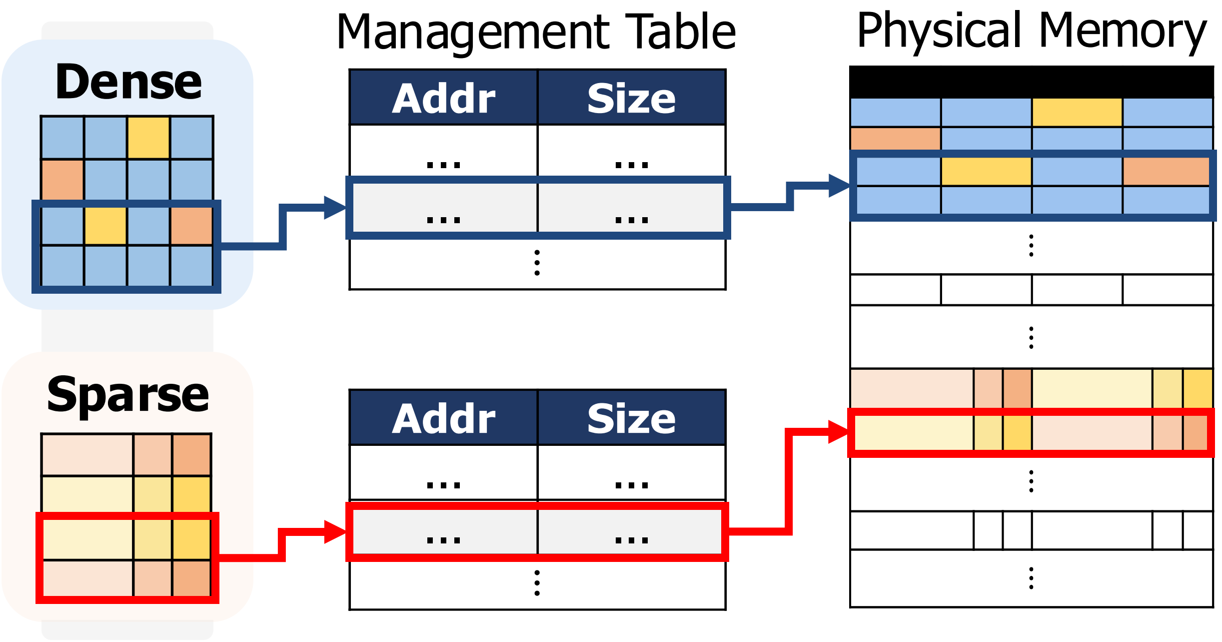
** Synthesized on TSMC 28nm*

- Oaken modules do **not modify** the existing compute logic in the accelerator
- Oaken modules are integrated into existing accelerator **with low overhead**

Oaken Hardware Modules



Quantization Engine



Memory Management Unit

- Oaken modules are designed to maximize **hardware** and **memory utilization**

Evaluation Methodology

- **Models**
  - Llama2 – 7B, 13B, 70B*
  - OPT – 6.7B, 13B, 30B*
  - Mistral – 7B
  - Mixtral – 8x7B*

  ** Used **2 GPUs** with pipeline parallelism*

- **Baselines**
  - Tender (ASIC)
  - Atom (GPU)
  - QServe (GPU)
  - KIVI (GPU)
  - KVQuant (GPU)

- **Datasets**
  - WikiText2, PIQA, WinoGrande, and HellaSwag

- **Group Configuration**
  - **4%, 90%, 6%** for outer, middle and inner group

- **Hardware Specification**

	NVIDIA A100	Oaken-HBM	Oaken-LPDDR
FP16 TFLOPS	312	270	270
Memory type	HBM	HBM	LPDDR
Memory capacity	80 / 160* GB	80 GB	256 GB
Memory bandwidth	2.0 TB/s	2.0 TB/s	1.1 TB/s

** Used **2 GPUs** with pipeline parallelism*

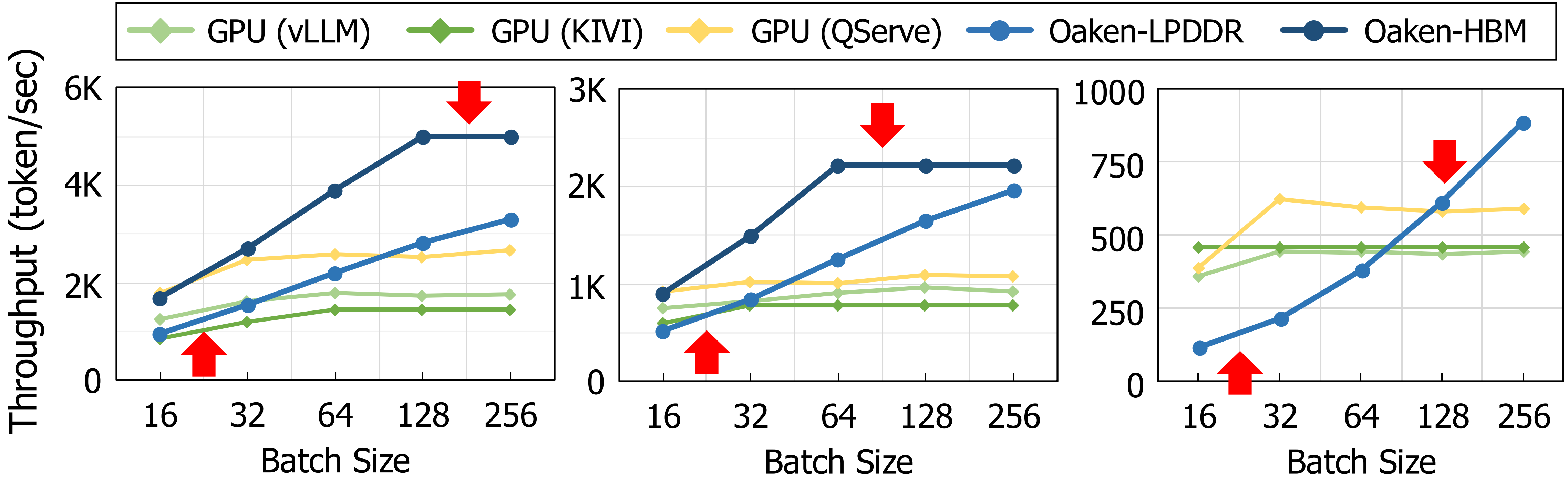
Evaluation Results

Throughput

Oaken-HBM achieves performance improvement of **1.79×** over vLLM (FP16)

Oaken-LPDDR is also a competitive option for **larger models** and **larger batches**

** Context length : 2K*



(1) Llama2-7B **(2) Llama2-13B** **(3) Llama2-70B**

Evaluation Results

Accuracy

Model	Llama2							
	13B	70B	13B	70B	13B	70B	13B	70B
Dataset	WikiText2		PIQA		WinoGrande		HellaSwag	
Metric	Perplexity (↓)		Accuracy (%)		Accuracy (%)		Accuracy (%)	
Original	**4.88**	**3.32**	**80.52**	**82.70**	**72.80**	**80.20**	**79.38**	**83.82**
KIVI	**4.90**	**3.33**	79.05	78.07	**70.96**	**76.81**	**78.97**	83.47
QServe*	5.12	3.36	77.48	81.77	66.80	76.09	76.69	83.24
Oaken	4.93	3.34	**79.71**	**82.59**	70.56	76.64	78.24	**83.50**

** Activated KV quantization feature only*

Oaken incurs **0.87%** and **0.32% accuracy loss** compared to FP16 and KIVI

Oaken achieves **1.38% higher** accuracy compared to QServe

Additional Results in Our Paper

- Performance evaluation using other LLMs and baselines
- Accuracy and effective bits with varying group configurations
- End-to-end latency breakdown
- Sensitivity study to total sequence length
- Performance evaluation using real-world benchmark
- Synthesized area and power

Conclusion

- **Oaken**
  - Acceleration solution for LLM inference serving including algorithm-hardware co-designed KV cache quantization technique
- **Contributions**
  - Addresses memory bandwidth and capacity bottlenecks in modern LLM serving
  - Finds sweet spot in accuracy-performance trade-off of KV cache quantization
- **Future works**
  - Extending Oaken to handle recent attention architectures *(e.g., latent attention, linear attention)*
  - HyperAccel's high efficiency LLM accelerator with broad quantization support