

LLM Sys

GPU Programming

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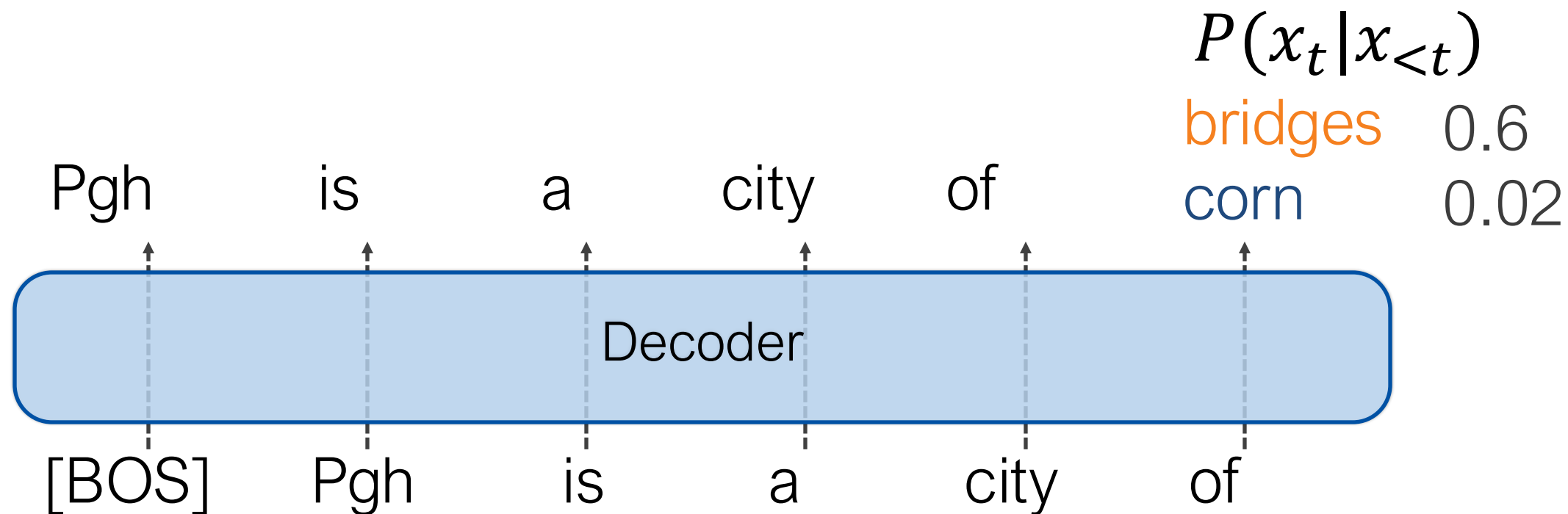


Carnegie Mellon University

Language Technologies Institute

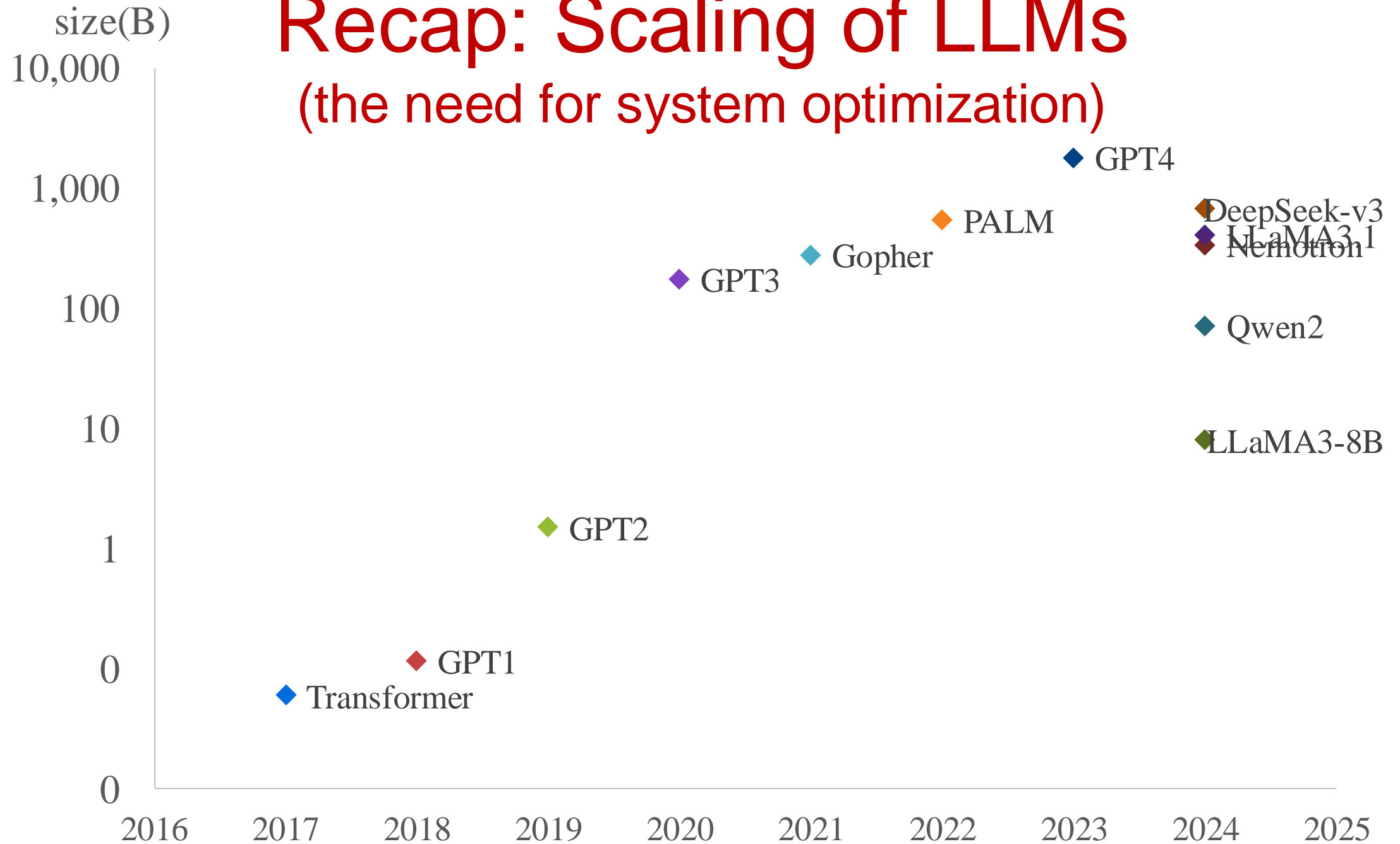
Recap: Language Model

$$P(x_{1..T}) = \prod_{t=1}^T P(x_{t+1} | x_{1..t})$$



Recap: Scaling of LLMs

(the need for system optimization)



Recap: Important Topics in LLM systems

- Programming model
 - relies on good abstraction
- Latency/Throughput
 - Data movement
 - Computation
- Reliability
- Security

Outline

- ➡ • GPU Architecture Overview
 - components of a GPU server
 - Comparison of Processors
 - GPU components and physical limits
 - How are programs executed on GPU?

Text Classification

Classifying the sentiment of online movie reviews. (Positive, negative, neutral)

Spider-Man is an almost-perfect extension of the experience of reading comic-book adventures.

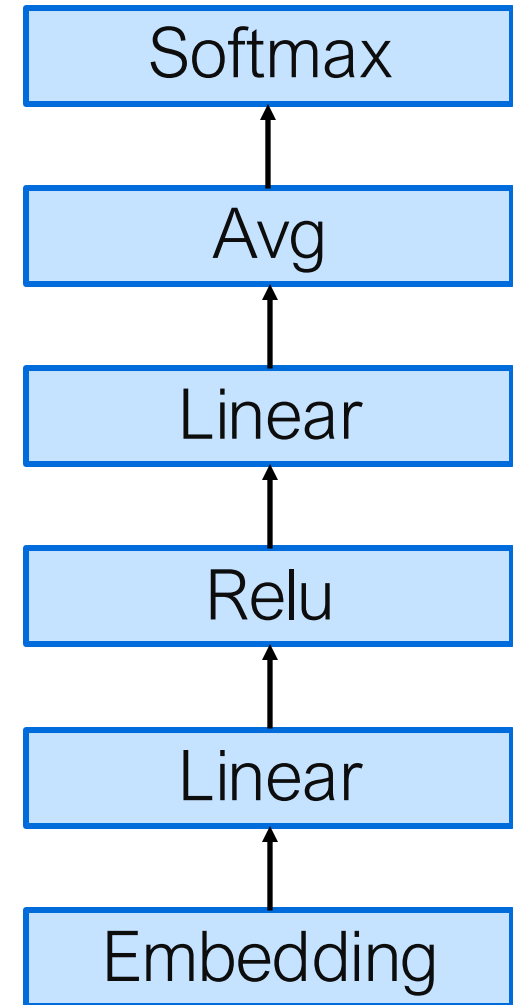


It was a boring! It was a waste of a movie to even be made. It should have been called a family reunion.



A Simple Feedforward Neural Network

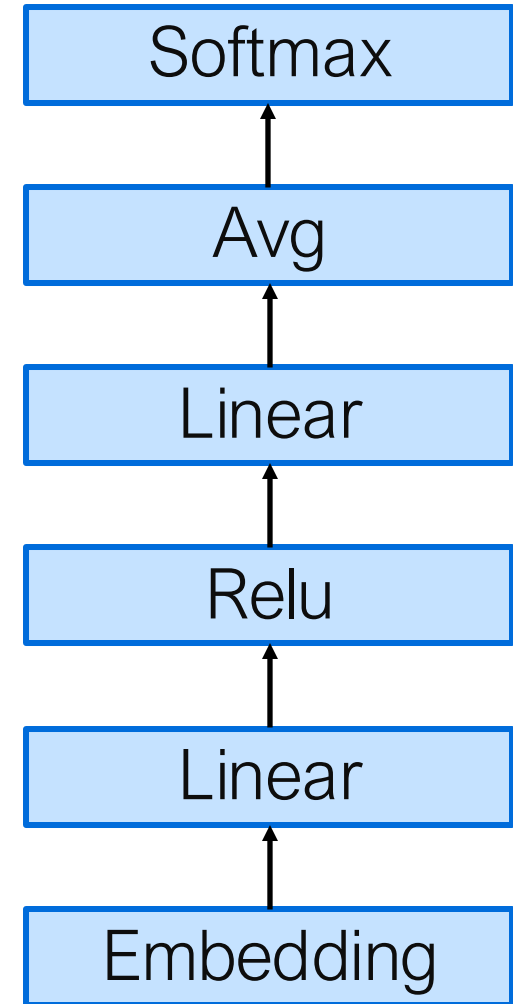
- Neural network layers
 - Embedding (lookup table)
 - Linear
 - Relu
 - Average pooling
 - Softmax



“It is a good movie”

Low-level Computing Operators

- Matrix multiplication
- Element-wise ops (add, scale, relu)
- Reduce ops (sum, avg)
- Efficient computation requires GPUs

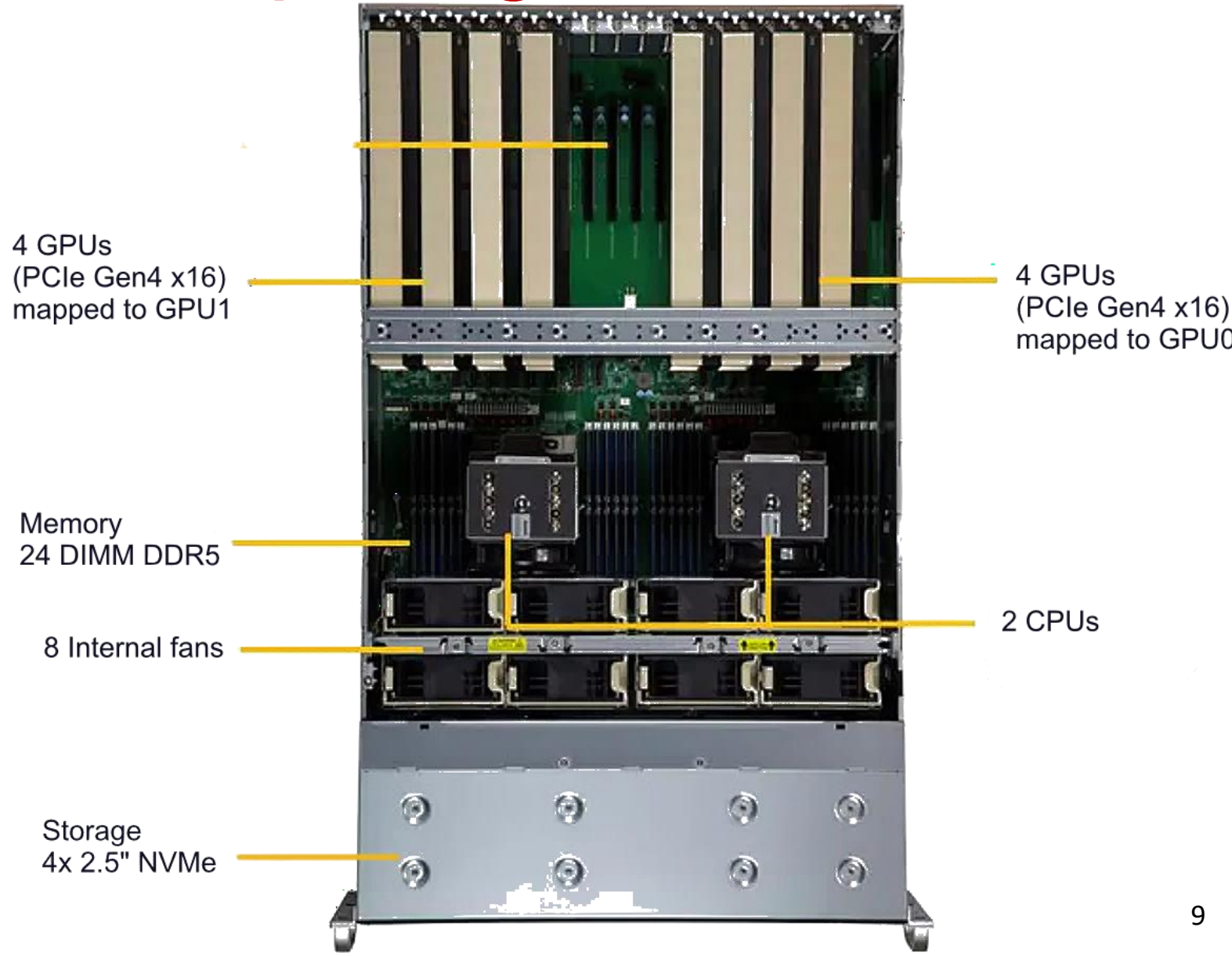


“It is a good movie”

A Modern Computing Server

A Sample Config (my lab)

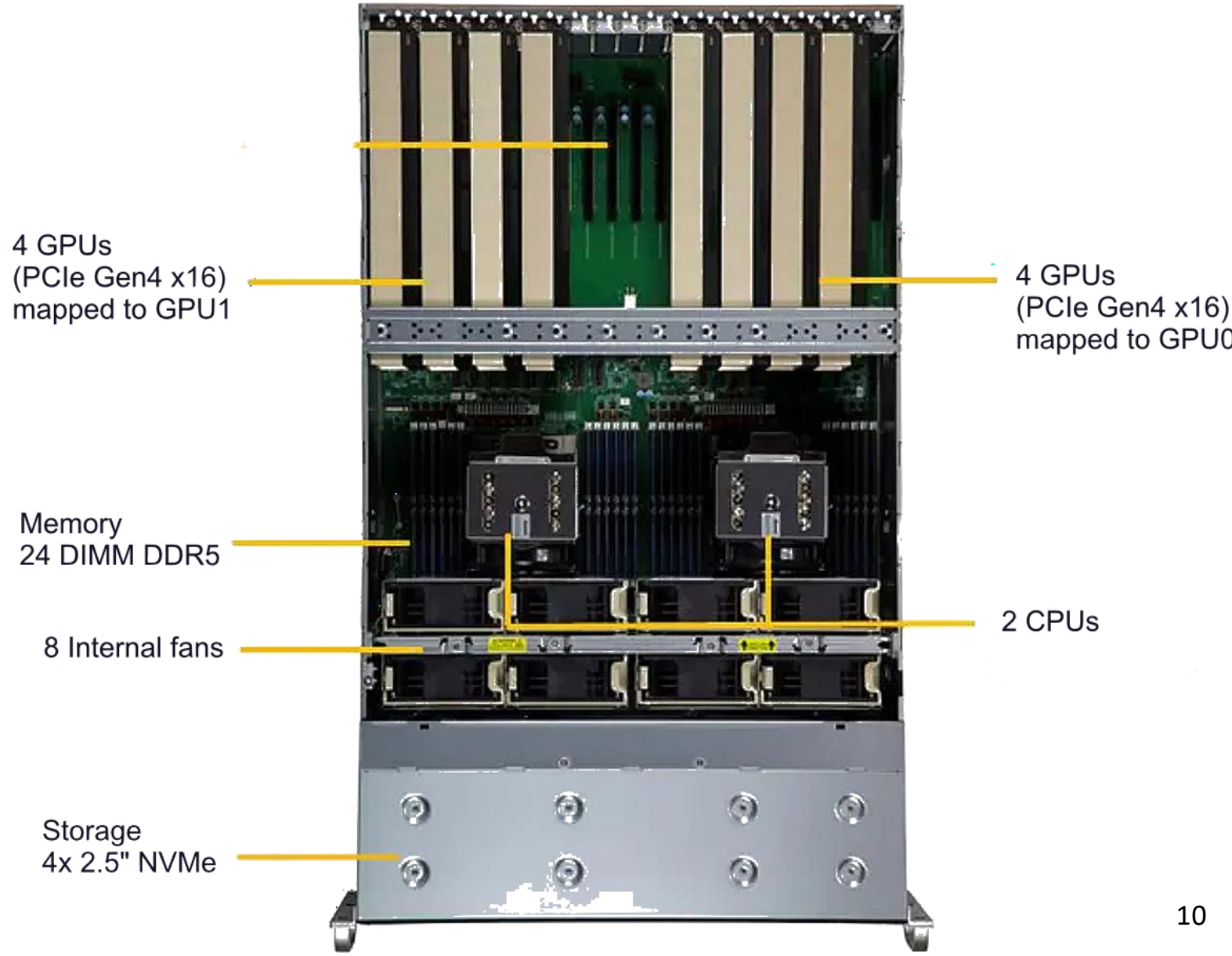
- CX4860s-EK9 4U server
- 2x AMD EPYC 9354 CPU
- 16x 64GB DDR5 mem
- 4x Intel D7 P5520
- 15.36TB Gen4 NVMe SSD
- 8x Nvidia A6000 48GB
- 4x 2slot NVLink



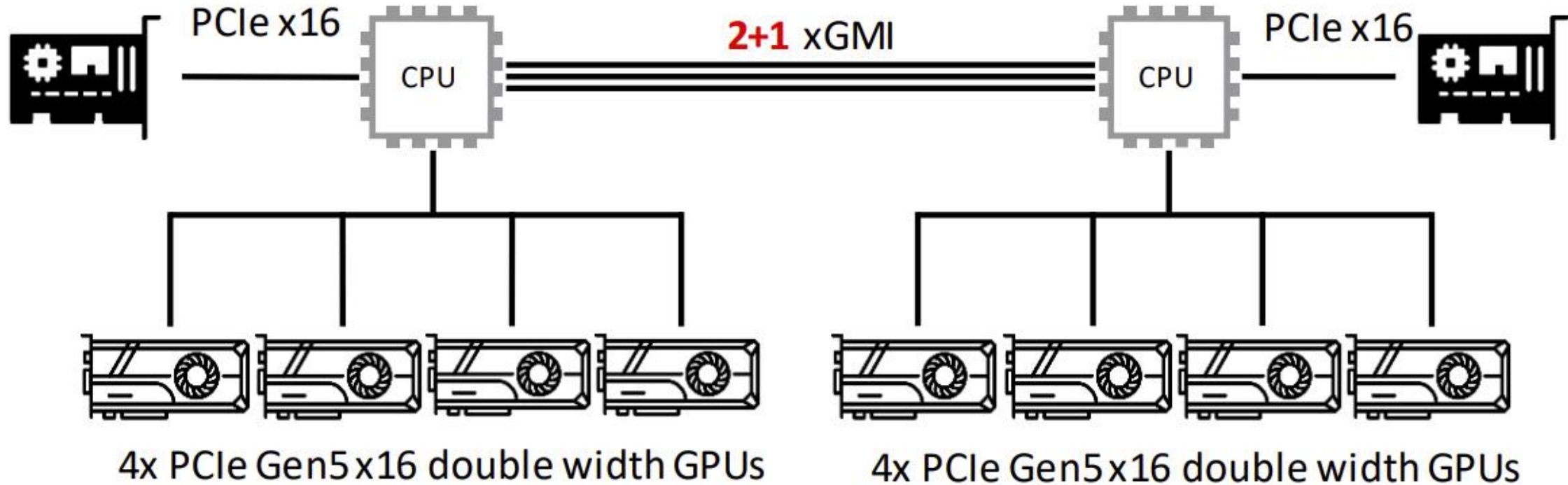
Communication

GPU-to-GPU

- NVLink 112.5 GB/s
- PCIe Gen4 32 GB/s (16 lanes x 2 GB/s per lane)



Modern Computing Server Architecture



Why is it relevant?

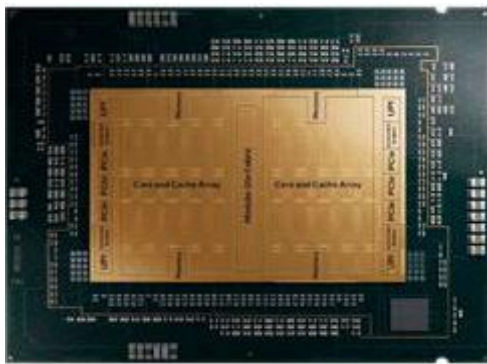
Considering moving gradients from one GPU to another

Computing Devices

CPU



AMD EPYC 9754
128cores
256threads
2.25GHz
256MB L3



Intel Xeon
8593Q
64cores
128threads
2.2GHz
320MB L3

GPU



Nvidia A6000
10,752 cores
48GB
38.7 TFLOPS

FPGA



More powerful than the #1
supercomputer in 2001

GPU Lineup

| Architecture | Blackwell | Hopper | Ampere |
|-----------------------|---------------|----------------|----------------|
| GPU Name | NVIDIA B200 | NVIDIA H100 | NVIDIA A100 |
| FP64 | 40 teraFLOPS | 34 teraFLOPS | 9.7 teraFLOPS |
| FP64 Tensor Core | 40 teraFLOPS | 67 teraFLOPS | 19.5 teraFLOPS |
| FP32 | 80 teraFLOPS | 67 teraFLOPS | 19.5 teraFLOPS |
| FP32 Tensor Core | 2.2 petaFLOPS | 989 teraFLOPS | 312 teraFLOPS |
| FP16/BF16 Tensor Core | 4.5 petaFLOPS | 1979 teraFLOPS | 624 teraFLOPS |
| INT8 Tensor Core | 9 petaOPs | 3958 teraOPs | 1248 teraOPs |
| FP8 Tensor Core | 9 petaFLOPS | 3958 teraFLOPS | - |
| FP4 Tensor Core | 18 petaFLOPS | - | - |
| GPU Memory | 192GB HBM3e | 80GB HBM3 | 80GB HBM2e |
| Memory Bandwidth | Up to 8TB/s | 3.2TB/s | 2TB/s |

GPU Architecture

Nvidia RTX A6000
(GA102)
84 SMs
(Streaming
Multiprocessors)
12 memory
controller (32bit
ea.) total 384bit.
6MB L2 cache.



Streaming Multiprocessor

4 partitions per SM, each with 32 cores → 32 threads each

128 cores per SM

64KB register per partition (fastest to access)

128KB shared L1 cache per SM

128 FP32 operations in one cycle



CPU vs. GPU

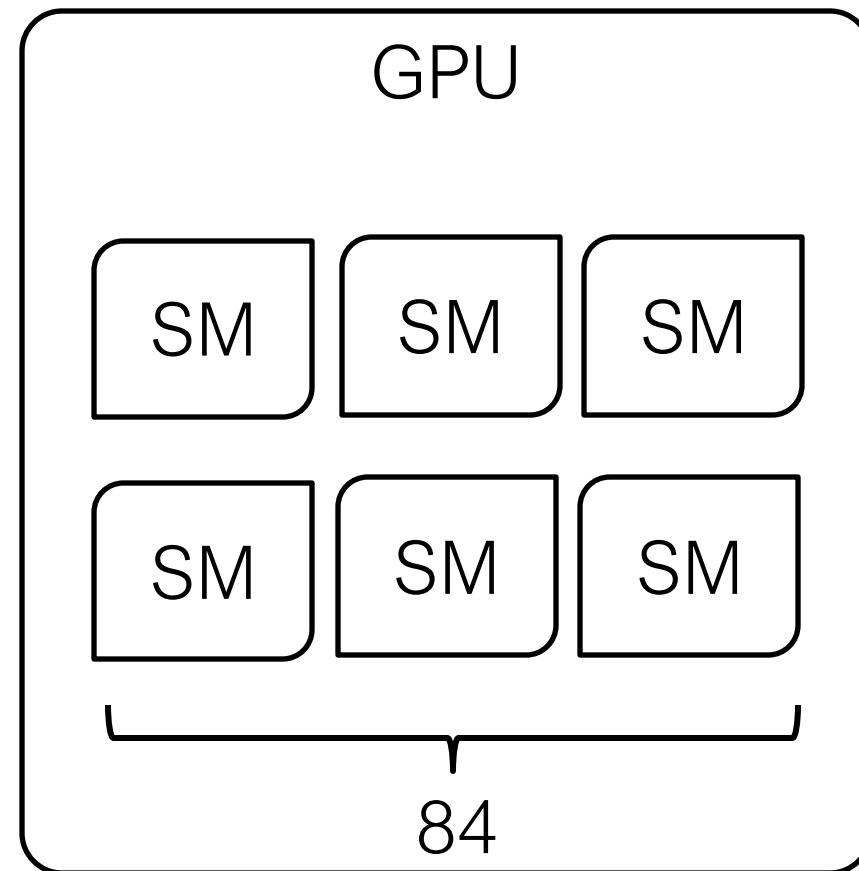
| | CPU (AMD EPYC 9754) | GPU (A6000) |
|--------------|---------------------|-------------|
| num. threads | 256 | 10752 |
| clock | 2.25 GHz | 1.8 GHz |
| compute | 576 GFlops | 38.7 TFlops |
| Power | 360W | 300W |

GPU Programming Model

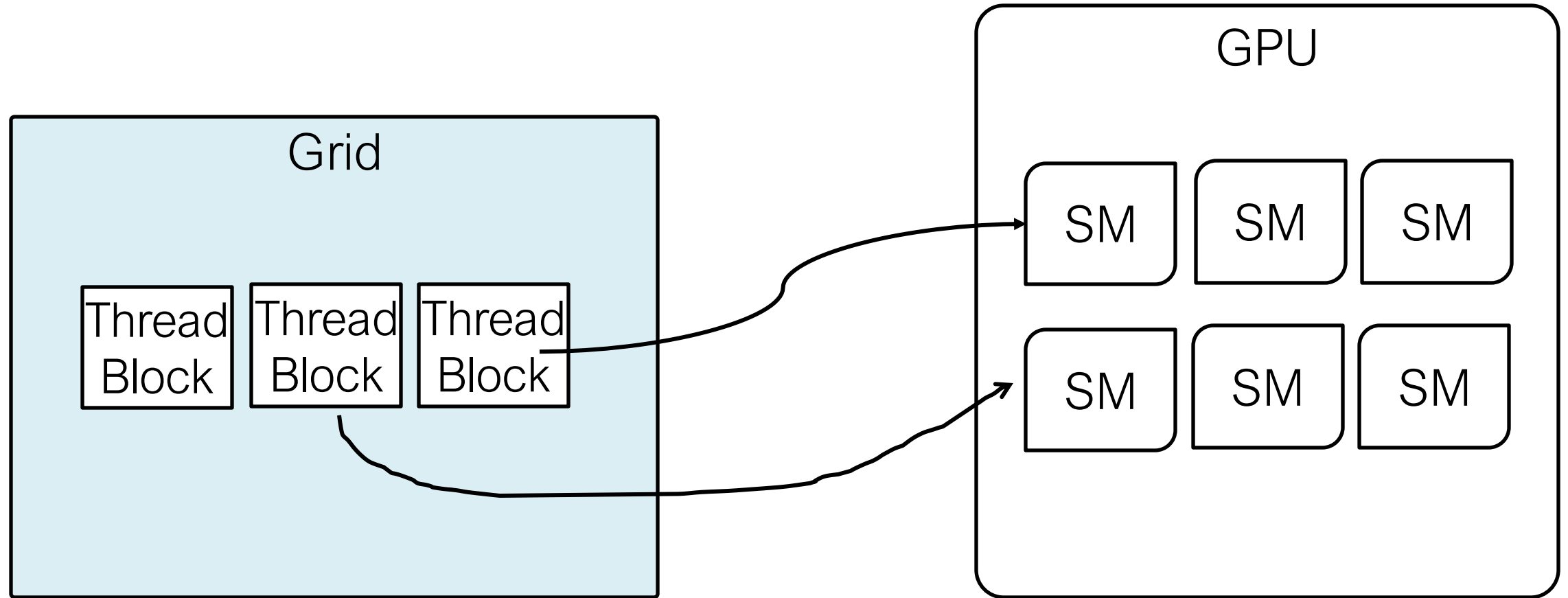
- CPU – host
 - Run normal program (C++)
- GPU – device
 - Run cuda kernel code
- CUDA: one part runs on CPU, one part runs on GPU
- Needs to move data between system memory and GPU memory

SIMT Execution on GPU

- Single Instruction Multiple Threads
- Threads are grouped into Thread Blocks
- Thread Blocks are grouped into Grid
- Kernel executed as Grid of Blocks of Threads



How instructions are executed on GPU



How Kernel Threads are Executed

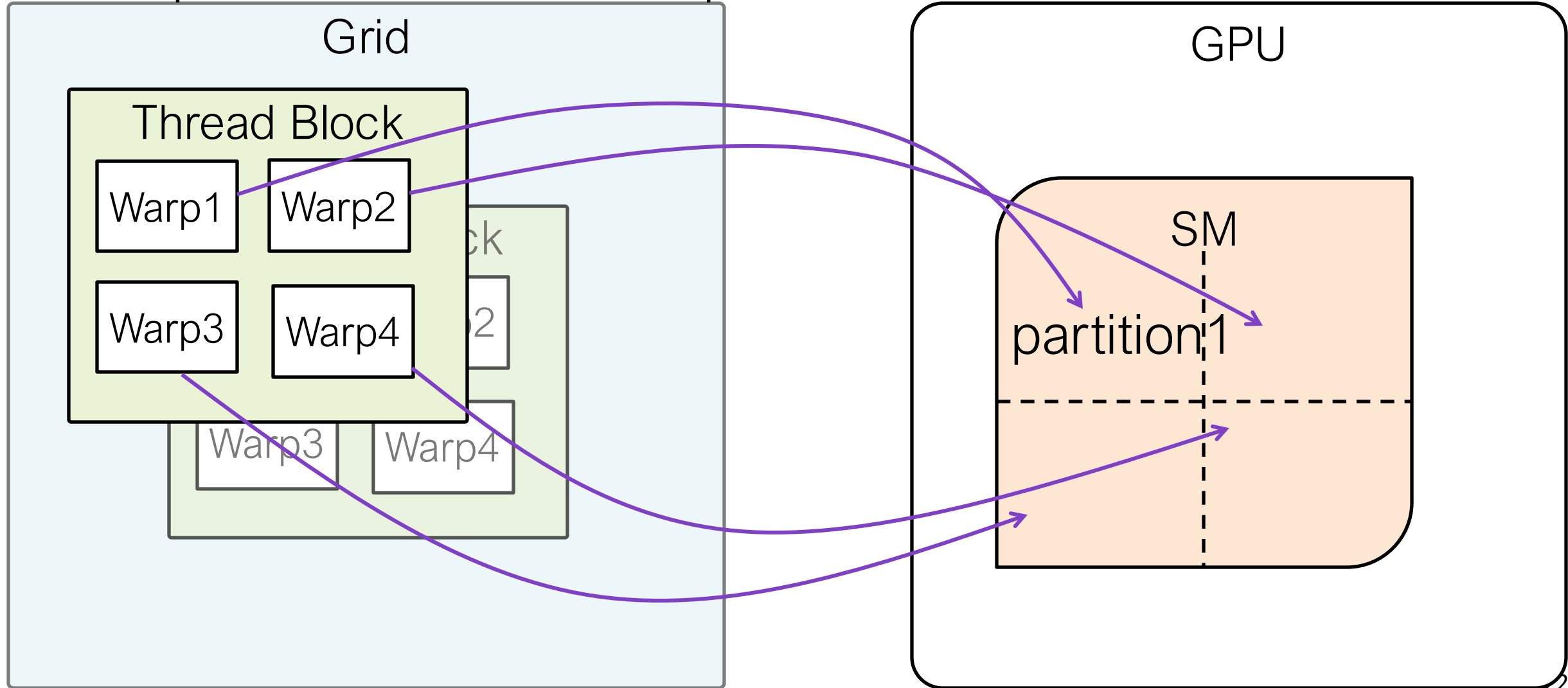
- SM partition a thread block into warps
- Warp is the unit of GPU creating, managing, scheduling and executing threads
- Each warp contains **32** threads (why 32?)
 - Start at same program address
 - Have own program counter and registers
 - Execute one common instruction at a cycle
 - Can branch and execute independently

Warp Execution on GPU

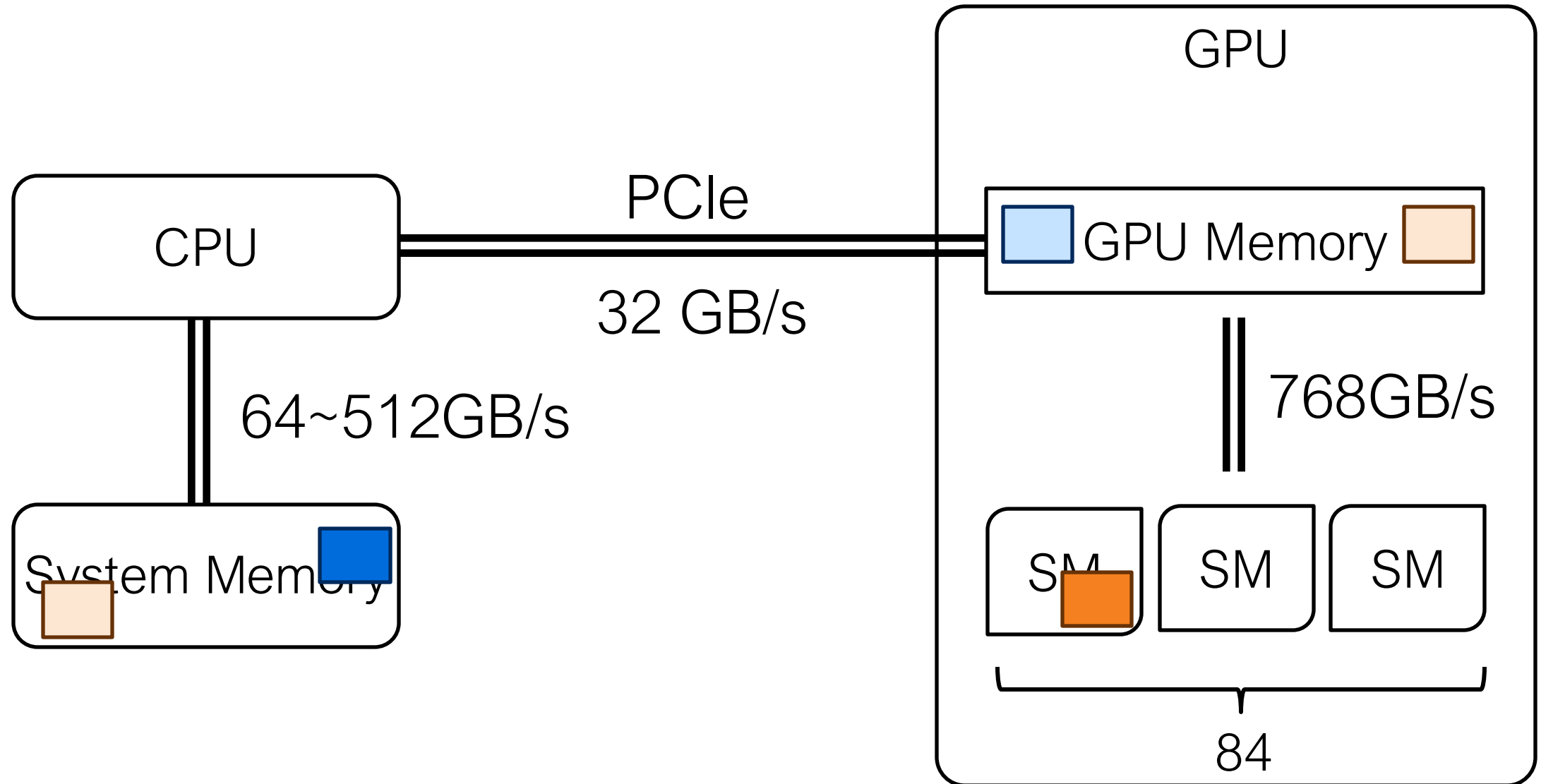
- Execution context stays on SM for lifetime of warp (Program counter, Registers, Shared memory)
- Warp-to-warp context switch is instant
- At running time, warp scheduler
 - Chooses warp with active threads
 - Issues instruction to warp's threads
- Number of warps on SM depends on mem requested and available

Executing one Thread block on one SM

4 warps can be executed in parallel at one time on each SM



CPU-GPU Data Movement

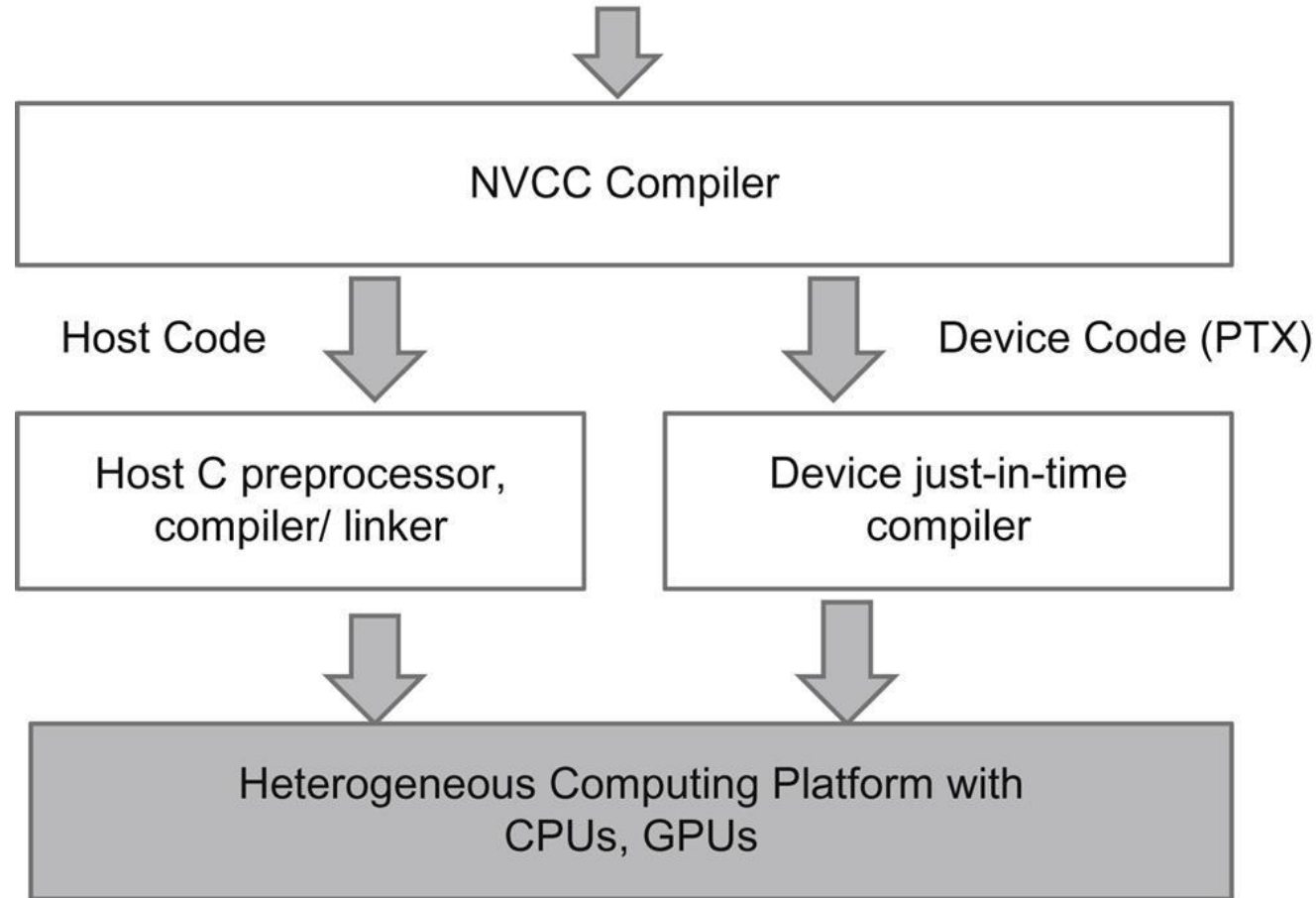


CUDA Kernel

- Each kernel is a function (program) that runs on GPU
- Program itself is serial
- Can simultaneously run many (10k) threads at the same time
- Using thread index to compute on right portion of data

Compiling CUDA Code

Integrated C programs with CUDA extensions



```
nvcc -o output.so --shared src.cu -Xcompiler -fPIC
```

Summary

- GPU is composed of
 - streaming processing units (SMs)
 - each with four partitions of 32 cores
 - shared L1 cache
 - memory
 - L2 cache: share with all SMs
- Threads organized in
 - grid of thread blocks
 - each block is divided into warps running on one SM.

Next

- Write GPU Programs

Assignment 1

https://lmsystem.github.io/lmsystem2025springhw/assignment_1/

Starter code: https://github.com/lmsystem/lmsys_s25_hw1.git

Due Feb 3

Quiz/Survey of Prior knowledge

<https://forms.gle/98RDShDfk3sVCCDr6>