THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING

RELAXED SYSTEM LAB

Tensor Model Parallel Training

COMP4901Y

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Tensor Model Parallelism

Recall Data & Pipeline Parallelism

- Data Parallelism:
  - **Memory issue**: each device needs to maintain a complete copy of the model (parameters, gradients, and optimizer status).
  - **Statistical efficiency**: if the global batch size is too large, it may affect the convergence rate
- Pipeline Parallelism:
  - **Bubble overhead:** the pipeline parallelism efficiency decreases as the number of stages increases.

TransformerBlocks$(x \in R^{B\times L\times D}) \rightarrow x' \in \mathbb{R}^{B\times L\times D}$

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- B is the batch size;
- L is the sequence length;
- D is the model dimension;
- Multi-head attention:
  $D = n_H \times H$
- H is the head dimension;
- n_h is the number of heads.

Computation	Input	Output
$Q = xW^Q$	$x \in \mathbb{R}^{B\times L\times D}$, $W^Q \in \mathbb{R}^{D\times D}$	$Q \in \mathbb{R}^{B\times L\times D}$
$K = xW^K$	$x \in \mathbb{R}^{B\times L\times D}$, $W^K \in \mathbb{R}^{D\times D}$	$K \in \mathbb{R}^{B\times L\times D}$
$V = xW^V$	$x \in \mathbb{R}^{B\times L\times D}$, $W^V \in \mathbb{R}^{D\times D}$	$V \in \mathbb{R}^{B\times L\times D}$
$[Q_1, Q_2 \dots, Q_{n_h}] = \text{Partion}_{-1}(Q)$	$Q \in \mathbb{R}^{B\times L\times D}$	$Q_i \in \mathbb{R}^{B\times L\times H}, i = 1, \dots n_h$
$[K_1, K_2 \dots, K_{n_h}] = \text{Partion}_{-1}(K)$	$K \in \mathbb{R}^{B\times L\times D}$	$K_i \in \mathbb{R}^{B\times L\times H}, i = 1, \dots n_h$
$[V_1, V_2 \dots, V_{n_h}] = \text{Partion}_{-1}(V)$	$V \in \mathbb{R}^{B\times L\times D}$	$V_i \in \mathbb{R}^{B\times L\times H}, i = 1, \dots n_h$
$\text{Score}_\text{i} = \text{softmax}(\frac{Q_i K_i^T}{\sqrt{D}}), i = 1, \dots n_h$	$Q_i, K_i \in \mathbb{R}^{B\times L\times H}$	$\text{score}_\text{i} \in \mathbb{R}^{B\times L\times L}$
$Z_i = \text{score}_i V_i, i = 1, \dots n_h$	$\text{score}_\text{i} \in \mathbb{R}^{B\times L\times L}$, $V_i \in \mathbb{R}^{B\times L\times H}$	$Z_i \in \mathbb{R}^{B\times L\times H}$
$Z = \text{Merge}_{-1}([Z_1, Z_2 \dots, Z_{n_h}])$	$Z_i \in \mathbb{R}^{B\times L\times H}, i = 1, \dots n_h$	$Z \in \mathbb{R}^{B\times L\times D}$
$\text{Out} = ZW^O$	$Z \in \mathbb{R}^{B\times L\times D}$, $W^O \in \mathbb{R}^{D\times D}$	$\text{Out} \in \mathbb{R}^{B\times L\times D}$
$A = \text{Out}\, W^1$	$\text{Out} \in \mathbb{R}^{B\times L\times D}$, $W^1 \in \mathbb{R}^{D\times 4D}$	$A \in \mathbb{R}^{B\times L\times 4D}$
$A' = \text{relu}(A)$	$A \in \mathbb{R}^{B\times L\times 4D}$	$A' \in \mathbb{R}^{B\times L\times 4D}$
$x' = A'W^2$	$A' \in \mathbb{R}^{B\times L\times 4D}$, $W^2 \in \mathbb{R}^{4D\times D}$	$x' \in \mathbb{R}^{B\times L\times D}$

Tensor Model Parallelism

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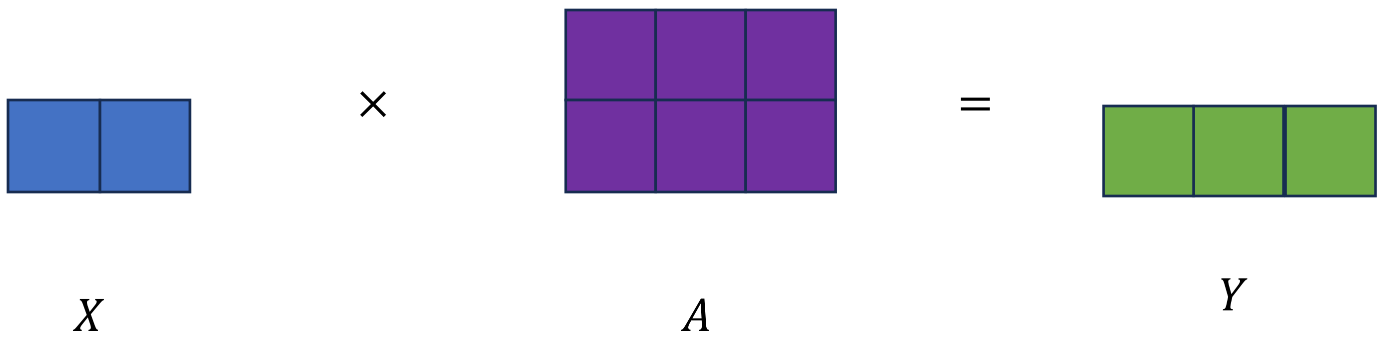
- High-level idea:
  - The tensor is split up into multiple chunks;
  - Instead of having the whole tensor reside on a single GPU, each shard of the tensor resides on its designated GPU.
  - Each shard is processed separately and in parallel on different GPUs.
  - The results are synchronized at the end of the step.

Partition the Matrix Multiplication

- Distribute the matrix multiplication:



Partition the Matrix Multiplication

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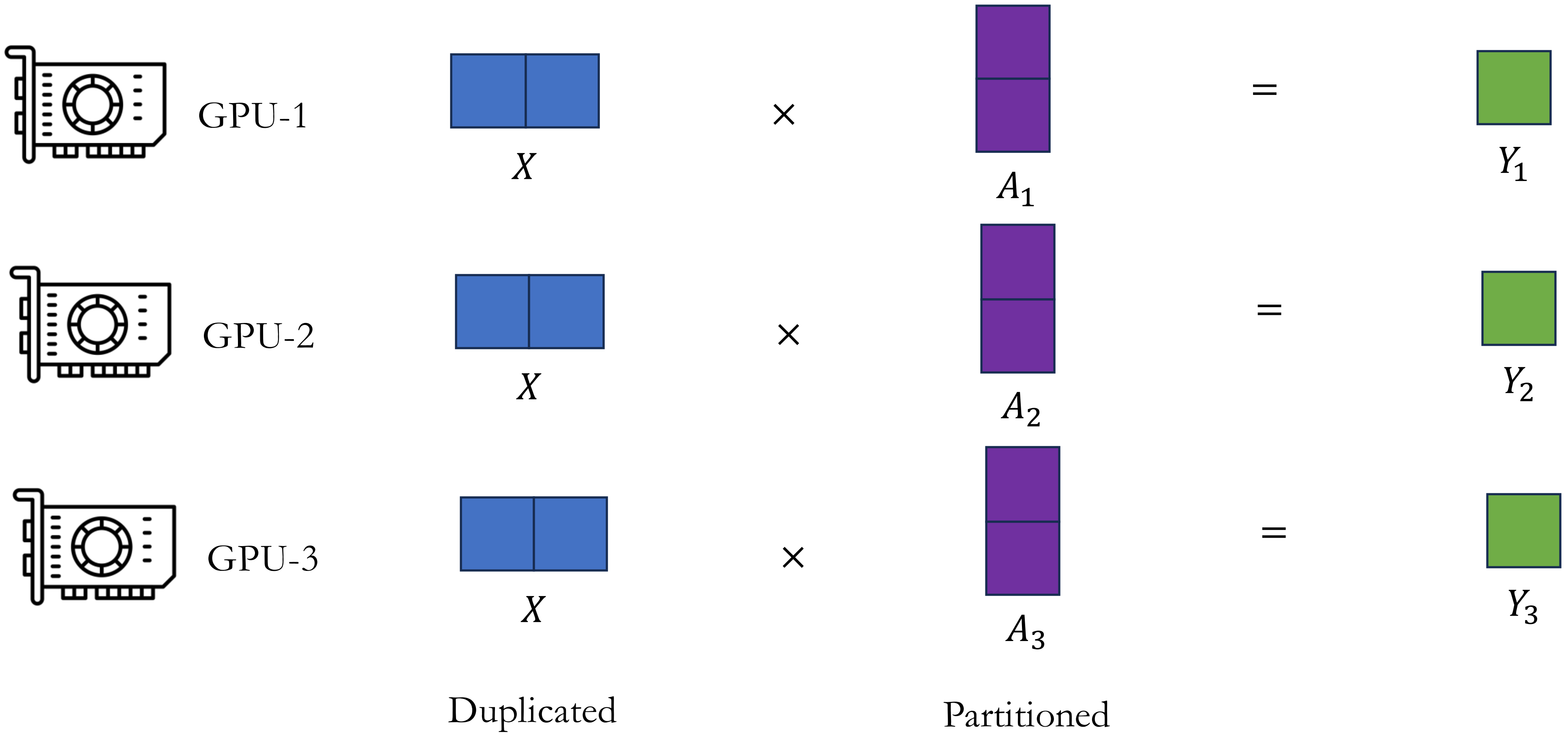

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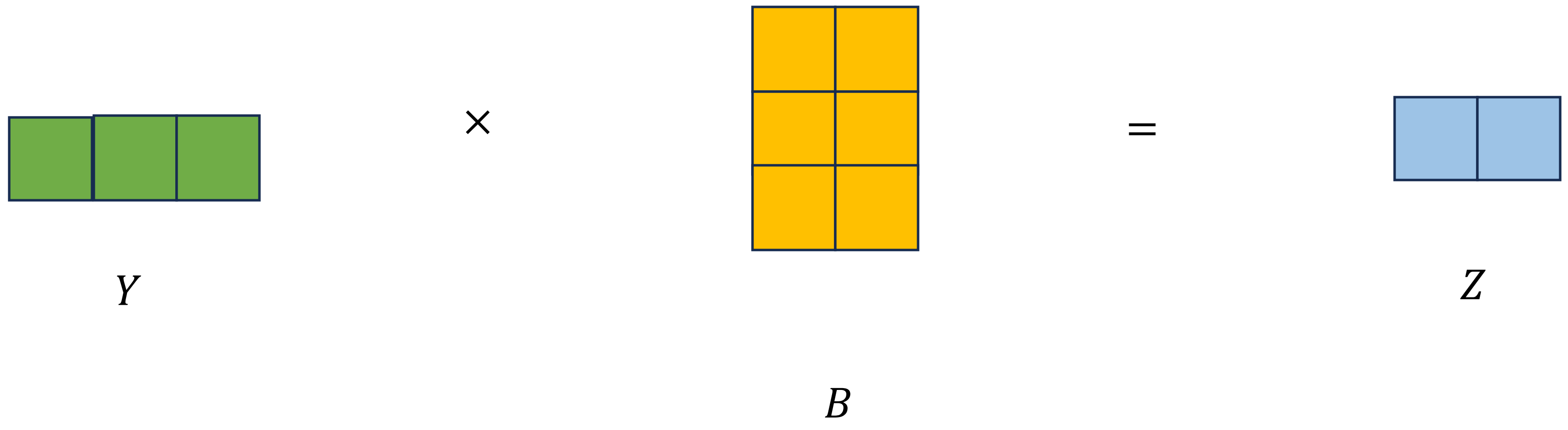

Partition the Matrix Multiplication

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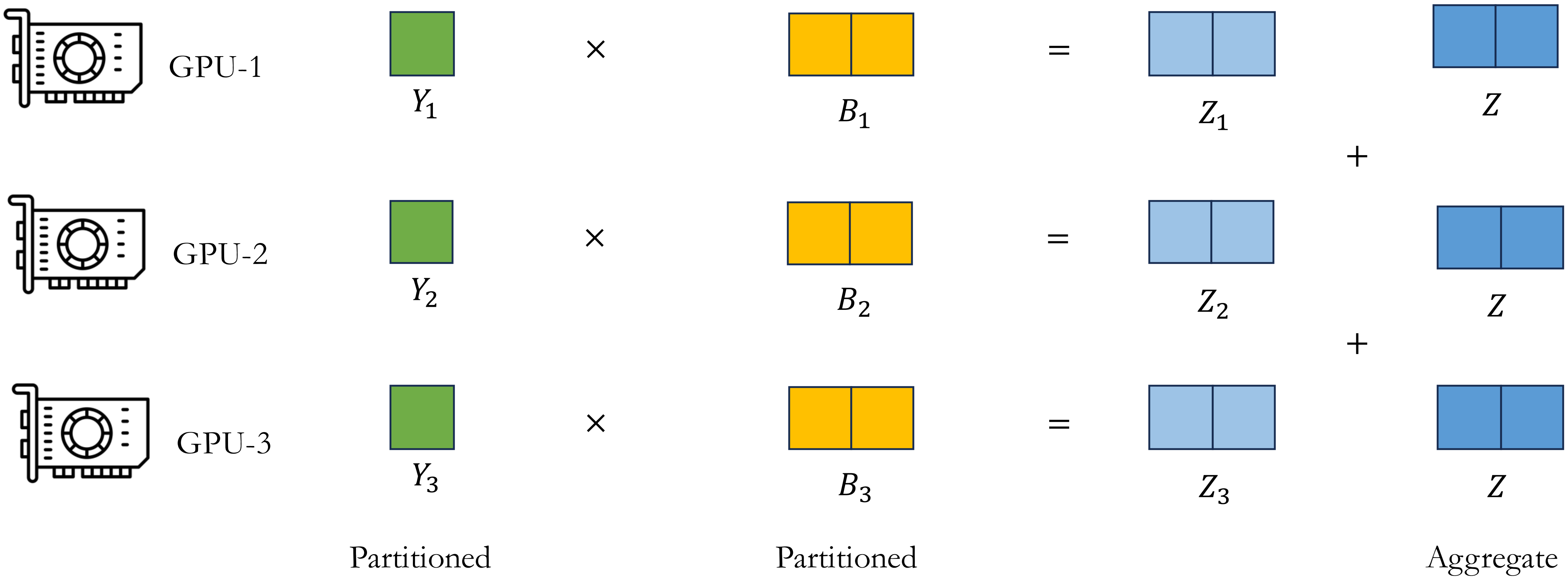
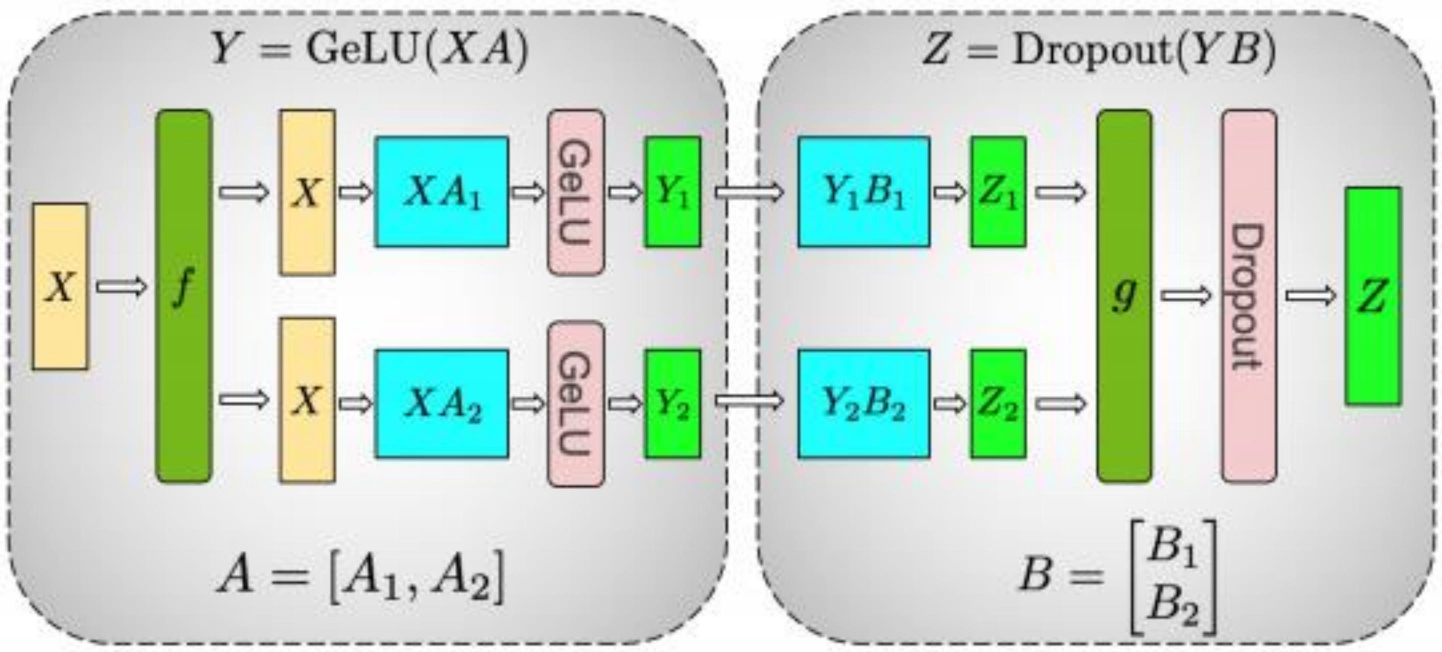


Tensor Model Parallelism

- Split the first weight matrix col-wisely;
- Split the second weight matrix row-wisely;
- Duplicate the input on each GPU;
- Apply the computation as we illustrated above;
- Aggregate the outputs after the local computation.

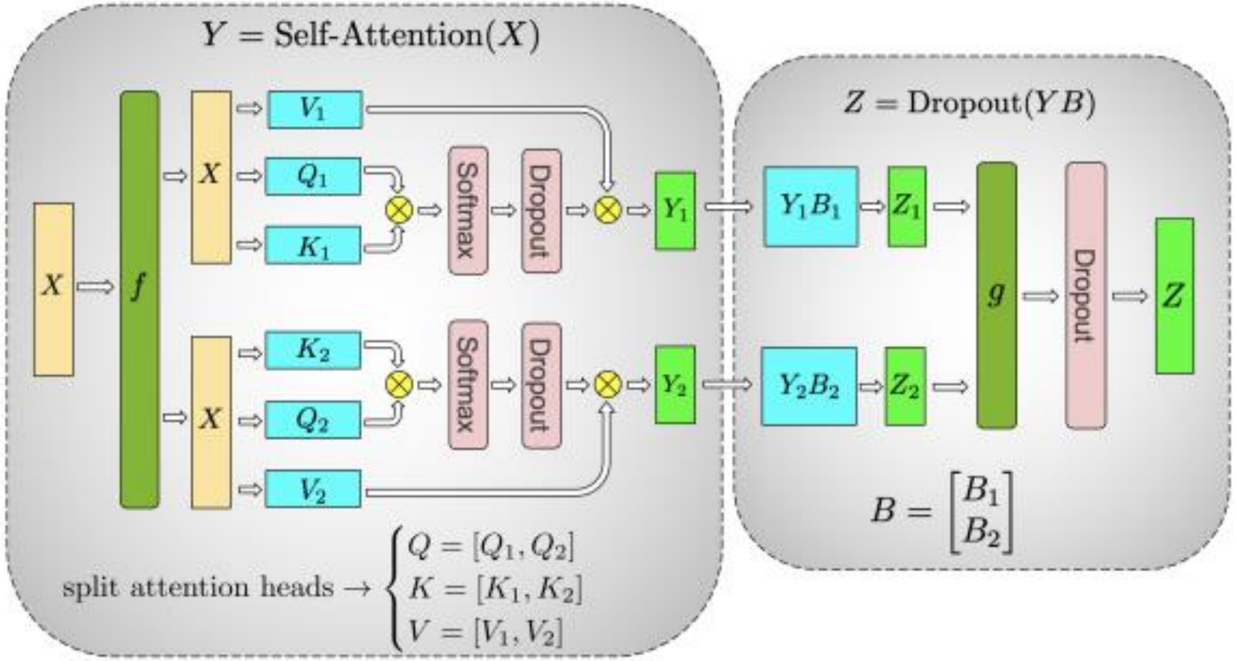
MLP in Tensor Model Parallelism



(a) MLP

- f is the identity operator in the forward pass and the AllReduce operator in the backward pass.
- g is the AllReduce operator in the forward pass and the identity operator in the backward pass.

Multi-Head Attention in Tensor Model Parallelism



(b) Self-Attention

- f is the identity operator in the forward pass and the AllReduce operator in the backward pass.
- g is the AllReduce operator in the forward pass and the identity operator in the backward pass.

TransformerBlocks in Tensor Model Parallelism

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- B is the batch size;
- L is the sequence length;
- D is the model dimension;
- Multi-head attention:
  $D = n_H \times H$
- H is the head dimension;
- n_H is the number of heads.
- d_{tp} is the tensor parallel degree: $d_{tp} \le n_H$.

Computation	Input	Output
$Q = xW^Q$	$x \in \mathbb{R}^{B\times L\times D}$, $W^Q \in \mathbb{R}^{D\times\frac{D}{d_{tp}}}$	$Q \in \mathbb{R}^{B\times L\times\frac{D}{d_{tp}}}$
$K = xW^K$	$x \in \mathbb{R}^{B\times L\times D}$, $W^K \in \mathbb{R}^{D\times\frac{D}{d_{tp}}}$	$K \in \mathbb{R}^{B\times L\times\frac{D}{d_{tp}}}$
$V = xW^V$	$x \in \mathbb{R}^{B\times L\times D}$, $W^V \in \mathbb{R}^{D\times\frac{D}{d_{tp}}}$	$V \in \mathbb{R}^{B\times L\times\frac{D}{d_{tp}}}$
$\left[Q_1, Q_2 \dots, Q_{\frac{n_H}{d_{tp}}}\right] = \text{Partion}_{-1}(Q)$	$Q \in \mathbb{R}^{B\times L\times\frac{D}{d_{tp}}}$	$Q_i \in \mathbb{R}^{B\times L\times H}, i = 1, \dots \frac{n_H}{d_{tp}}$
$\left[K_1, K_2 \dots, K_{\frac{n_H}{d_{tp}}}\right] = \text{Partion}_{-1}(K)$	$K \in \mathbb{R}^{B\times L\times\frac{D}{d_{tp}}}$	$K_i \in \mathbb{R}^{B\times L\times H}, i = 1, \dots \frac{n_H}{d_{tp}}$
$\left[V_1, V_2 \dots, V_{\frac{n_H}{d_{tp}}}\right] = \text{Partion}_{-1}(V)$	$V \in \mathbb{R}^{B\times L\times\frac{D}{d_{tp}}}$	$V_i \in \mathbb{R}^{B\times L\times H}, i = 1, \dots \frac{n_H}{d_{tp}}$
$\text{Score}_\text{i} = \text{softmax}(\frac{Q_i K_i^T}{\sqrt{D}}), i = 1, \dots \frac{n_H}{d_{tp}}$	$Q_i, K_i \in \mathbb{R}^{B\times L\times H}$	$\text{score}_\text{i} \in \mathbb{R}^{B\times L\times L}$
$Z_i = \text{score}_i V_i, i = 1, \dots \frac{n_H}{d_{tp}}$	$\text{score}_\text{i} \in \mathbb{R}^{B\times L\times L}$, $V_i \in \mathbb{R}^{B\times L\times H}$	$Z_i \in \mathbb{R}^{B\times L\times H}$
$Z = \text{Merge}_{-1}\left(\left[Z_1, Z_2 \dots, Z_{\frac{n_H}{d_{tp}}}\right]\right)$	$Z_i \in \mathbb{R}^{B\times L\times H}, i = 1, \dots \frac{n_H}{d_{tp}}$	$Z \in \mathbb{R}^{B\times L\times\frac{D}{d_{tp}}}$
$\text{Out} = ZW^O$	$Z \in \mathbb{R}^{B\times L\times\frac{D}{d_{tp}}}$, $W^O \in \mathbb{R}^{\frac{D}{d_{tp}}\times D}$	$\text{Out} \in \mathbb{R}^{B\times L\times D}$
AllReduce(Out)	$\text{Out} \in \mathbb{R}^{B\times L\times D}$	$\text{Out} \in \mathbb{R}^{B\times L\times D}$

TransformerBlocks in Tensor Model Parallelism

- B is the batch size;
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- Multi-head attention:
  $D = n_H \times H$
- H is the head dimension;
- n_H is the number of heads.
- d_{tp} is the tensor parallel degree: $d_{tp} \leq n_H$.

Computation	Input	Output
$A = \mathrm{Out}\, W^1$	$\mathrm{Out} \in \mathbb{R}^{B\times L\times D}$, $\mathrm{W}^1 \in \mathbb{R}^{D\times\frac{4D}{d_{tp}}}$	$A \in \mathbb{R}^{B\times L\times\frac{4D}{\mathrm{d}_{tp}}}$
$A' = \mathrm{relu}(A)$	$A \in \mathbb{R}^{B\times L\times\frac{4D}{\mathrm{d}_{tp}}}$	$A' \in \mathbb{R}^{B\times L\times\frac{4D}{\mathrm{d}_{tp}}}$
$x' = A'W^2$	$A' \in \mathbb{R}^{B\times L\times\frac{4D}{\mathrm{d}_{tp}}}$, $\mathrm{W}^2 \in \mathbb{R}^{\frac{4D}{d_{tp}}\times D}$	$x' \in \mathbb{R}^{B\times L\times D}$
AllReduce(x')	$x' \in \mathbb{R}^{B\times L\times D}$	$x' \in \mathbb{R}^{B\times L\times D}$

Tensor Model Parallelism in Megatron-LM

https://github.com/NVIDIA/Megatron-LM

Entrance of the Training Scripts

```
model = GPTModel(
    config=config,
    transformer_layer_spec=transformer_layer_spec,
    vocab_size=args.padded_vocab_size,
    max_sequence_length=args.max_position_embeddings,
    pre_process=pre_process,
    post_process=post_process,
    fp16_lm_cross_entropy=args.fp16_lm_cross_entropy,
    parallel_output=True,
    share_embeddings_and_output_weights=not args.untie_embeddings_and_output_weights,
    position_embedding_type=args.position_embedding_type,
    rotary_percent=args.rotary_percent,
)
```

https://github.com/NVIDIA/Megatron-LM/blob/main/pretrain_gpt.py#L60

Launch Scripts

```
GPT_ARGS="
    --tensor-model-parallel-size 2 \
    --pipeline-model-parallel-size 2 \
    --sequence-parallel \
    --num-layers 24 \
    --hidden-size 1024 \
    --num-attention-heads 16 \
    --seq-length 1024 \
    --max-position-embeddings 1024 \
    --micro-batch-size 4 \
    --global-batch-size 16 \
    --lr 0.00015 \
    --train-iters 500000 \
    --lr-decay-iters 320000 \
    --lr-decay-style cosine \
    --min-lr 1.0e-5 \
    --weight-decay 1e-2 \
    --lr-warmup-fraction .01 \
    --clip-grad 1.0 \
    --fp16
"
```

https://github.com/NVIDIA/Megatron-LM/blob/main/examples/pretrain_gpt_distributed_with_mp.sh#L28

References

- https://huggingface.co/transformers/v4.9.2/parallelism.html
- https://arxiv.org/abs/2104.04473
- https://github.com/NVIDIA/Megatron-LM/tree/main