System for Artificial Intelligence

Parallelization and Training I

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Recap: DNN Training Overview

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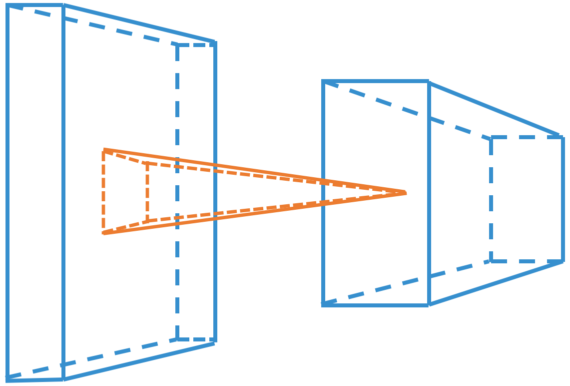
layer1
extractor

layer2
extractor



predictor

$$\hat{y}_i = \frac{1}{1 + \exp(-w^T x_i)}$$

Objective

$$L(w) = \sum_{i=1}^{n} l(y_i, \hat{y}_i) + \lambda ||w||^2$$

Training

$$w \leftarrow w - \boxed{\eta \nabla_w L(w)}$$

DNN Training Process

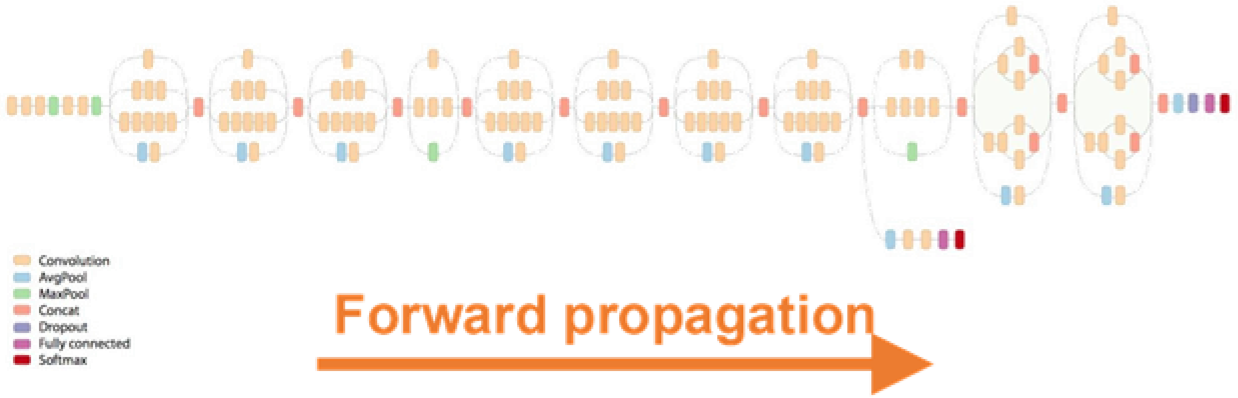
- Train ML models through many iterations of 3 stages

1. Forward propagation: apply model to a batch of input samples and run calculation through operators to produce a prediction

2. Backward propagation: run the model in reverse to produce error for each trainable weight

3. Weight update: use the loss value to update model weights

Model inputs



Model prediction

DNN Training Process

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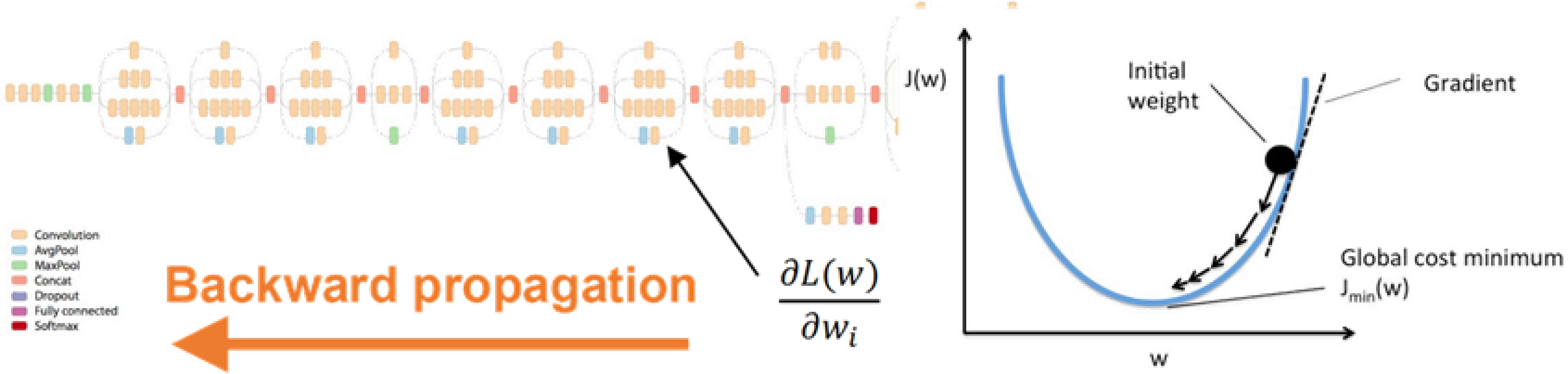

DNN Training Process

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- Train ML models through many iterations of 3 stages

1. Forward propagation: apply model to a batch of input samples and run calculation through operators to produce a prediction

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$$w_i := w_i - \gamma \frac{\partial L(w)}{\partial w_i} = w_i - \frac{\gamma}{n} \sum_{j=1}^{n} \boxed{\frac{\partial l_i(w)}{\partial w_i}}$$

Gradients of individual samples

How can we parallelize DNN training?

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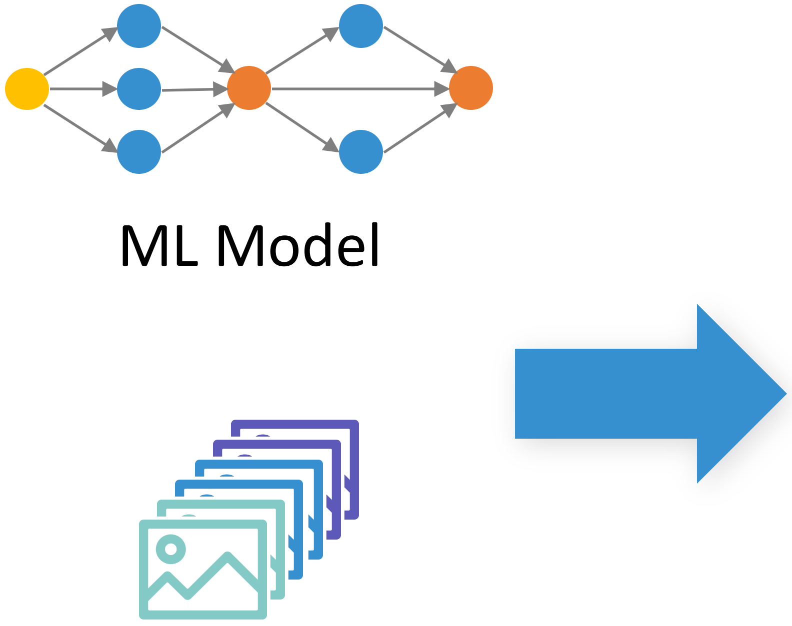
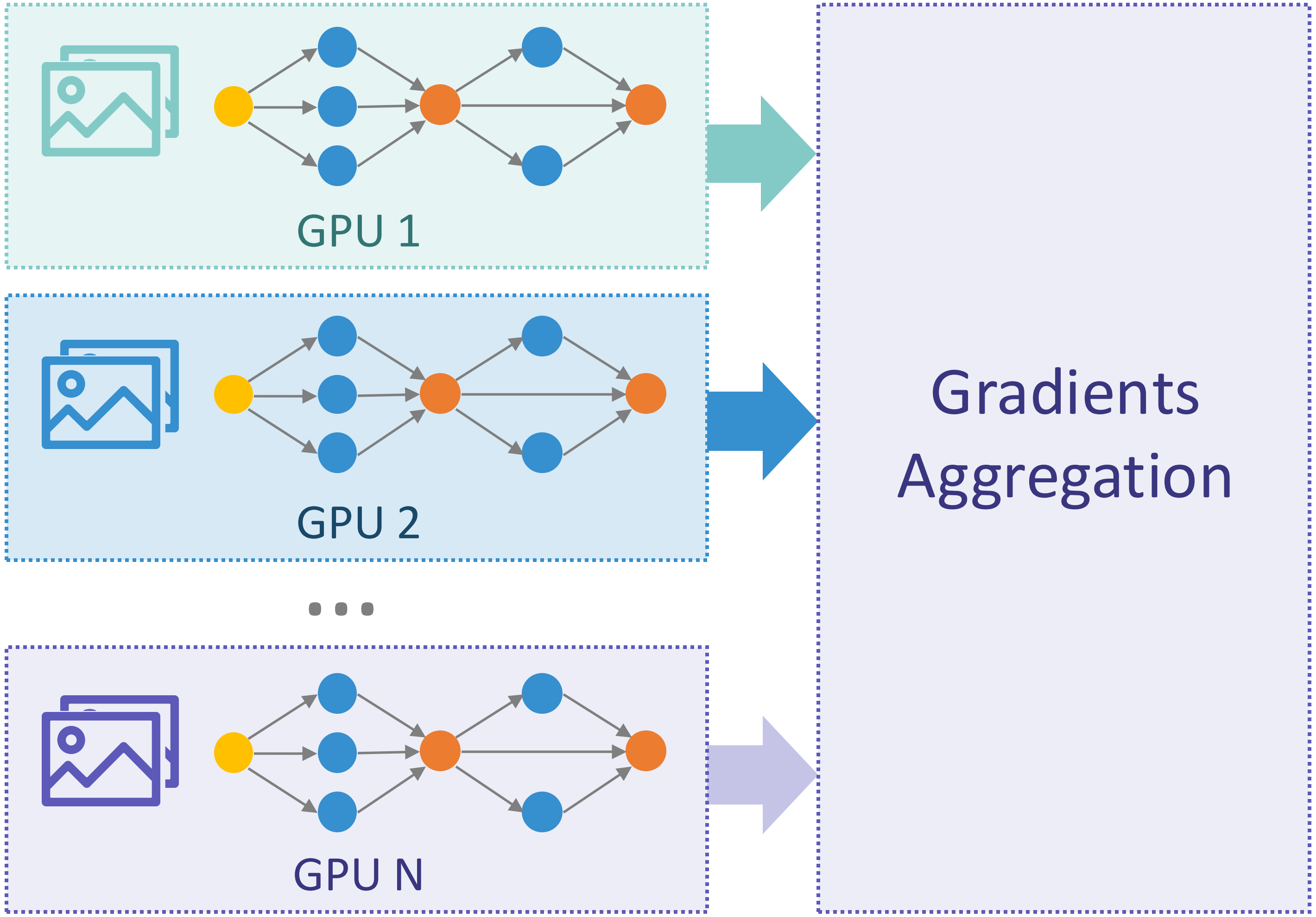
$$w_i \coloneqq w_i - \gamma \nabla L(w_i) = w_i - \frac{\gamma}{n} \sum_{j=1}^{n} \nabla L_j(w_i)$$

Data Parallelism



Training Dataset

$$w_i := w_i - \gamma \nabla L(w_i) = w_i - \frac{\gamma}{n} \boxed{\sum_{j=1}^{n} \nabla L_j(w_i)}$$

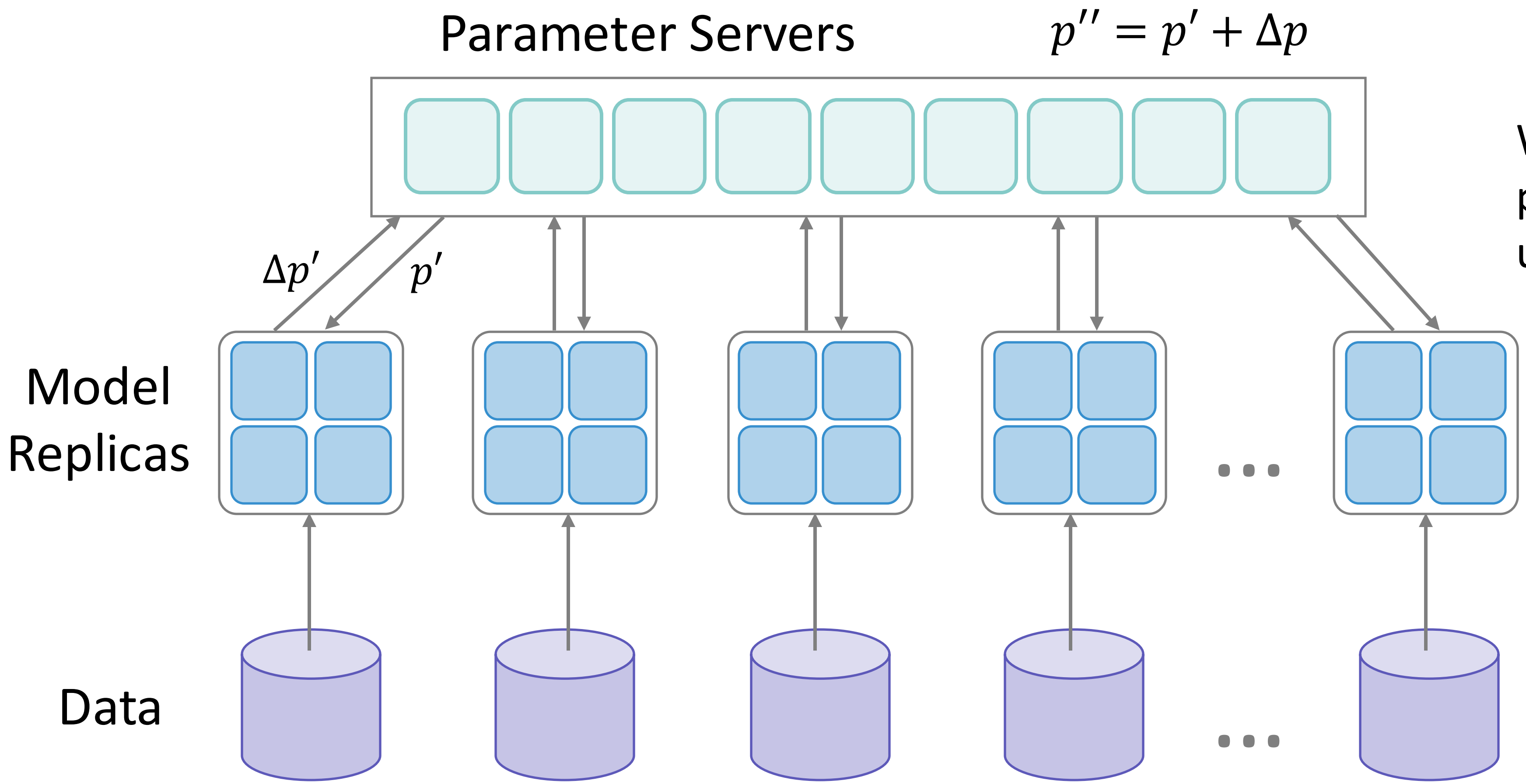


1. Partition training data into batches

2. Compute the gradients of each batch on a GPU

3. Aggregate gradients across GPUs

Data Parallelism: Parameter Server



Workers push gradients to parameter servers and pull updated parameters back

Inefficiency of Parameter Server

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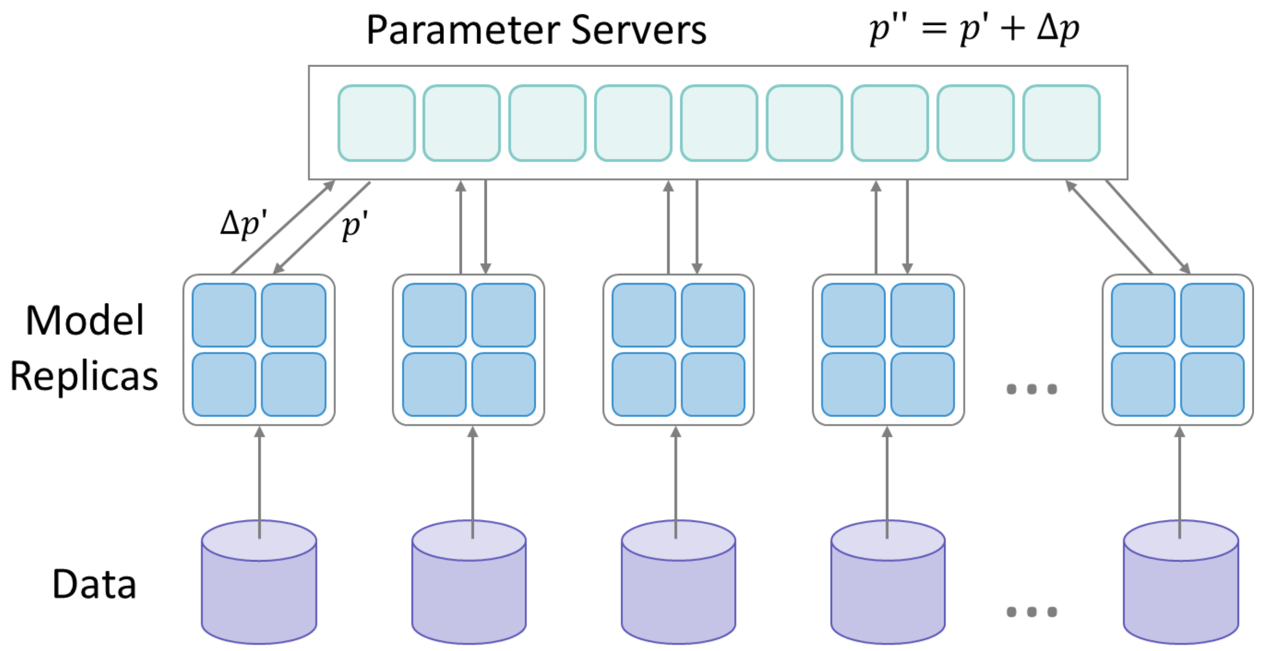
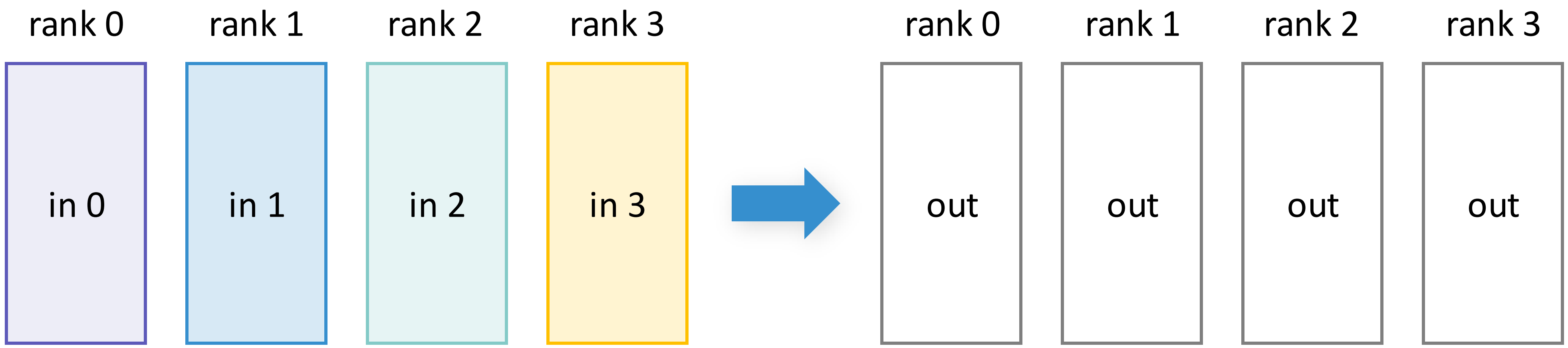
- **Centralized communication:** all workers communicate with parameter servers for weights update; cannot scale to large numbers of workers
- How can we decentralize communication in DNN training?



Inefficiency of Parameter Server

- **Centralized communication:** all workers communicate with parameter servers for weights update; cannot scale to large numbers of workers
- How can we decentralize communication in DNN training?
- **All-Reduce:** perform element-wise reduction across multiple devices



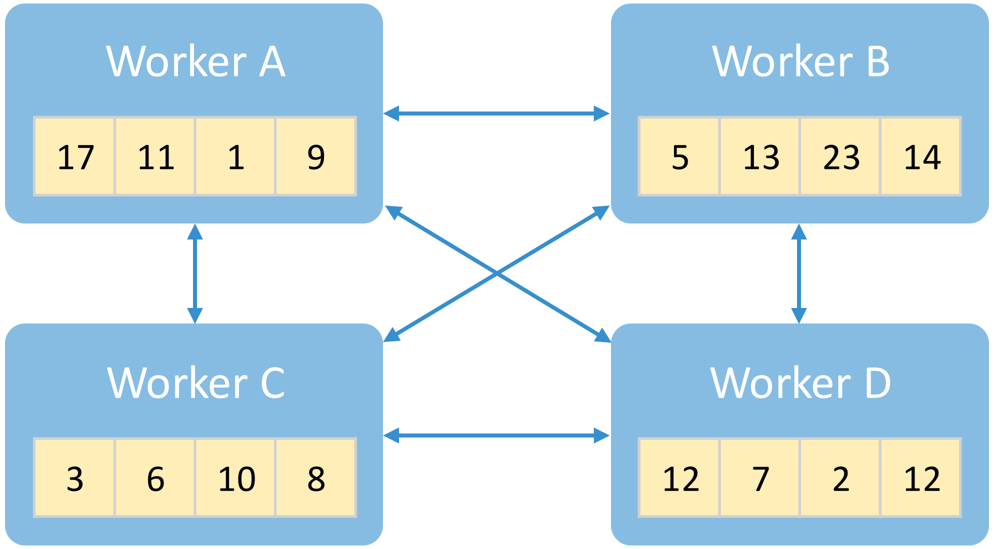
$$\mathrm{out}[i] = sum(\ln X\,[i])$$

Different Ways to Perform All-Reduce

- Naïve All-Reduce
- Ring All-Reduce
- Tree All-Reduce
- Butterfly All-Reduce

Naïve All-Reduce

- Each worker can send its local gradients to all other workers
- If we have N workers and each worker contains M parameters
- Overall communication: N * (N-1) * M parameters
- **Issue**: each worker communicates with all other workers; same scalability issue as parameter server



Ring All-Reduce

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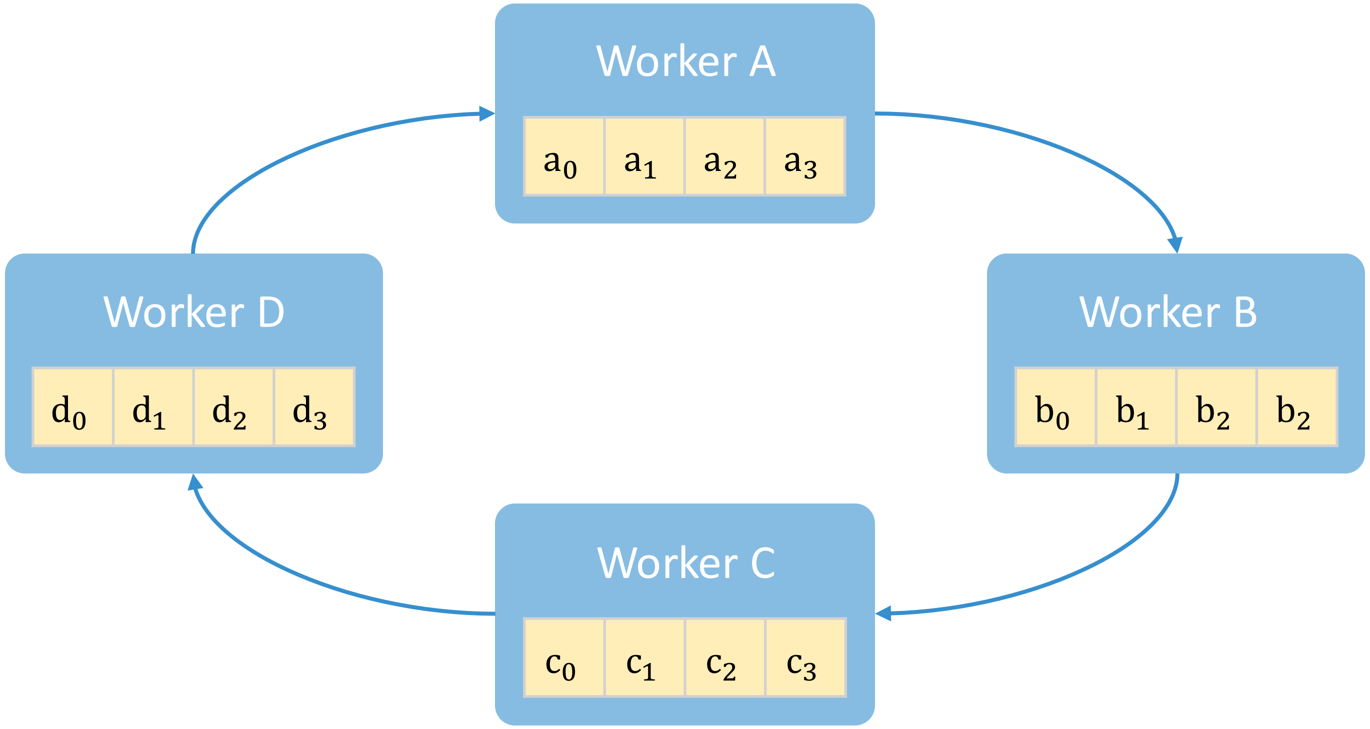
- Construct a ring of N workers, divide M parameters into N slices
- Step 1 (Aggregation): each worker send one slice (M/N parameters) to the next worker on the ring; repeat N times



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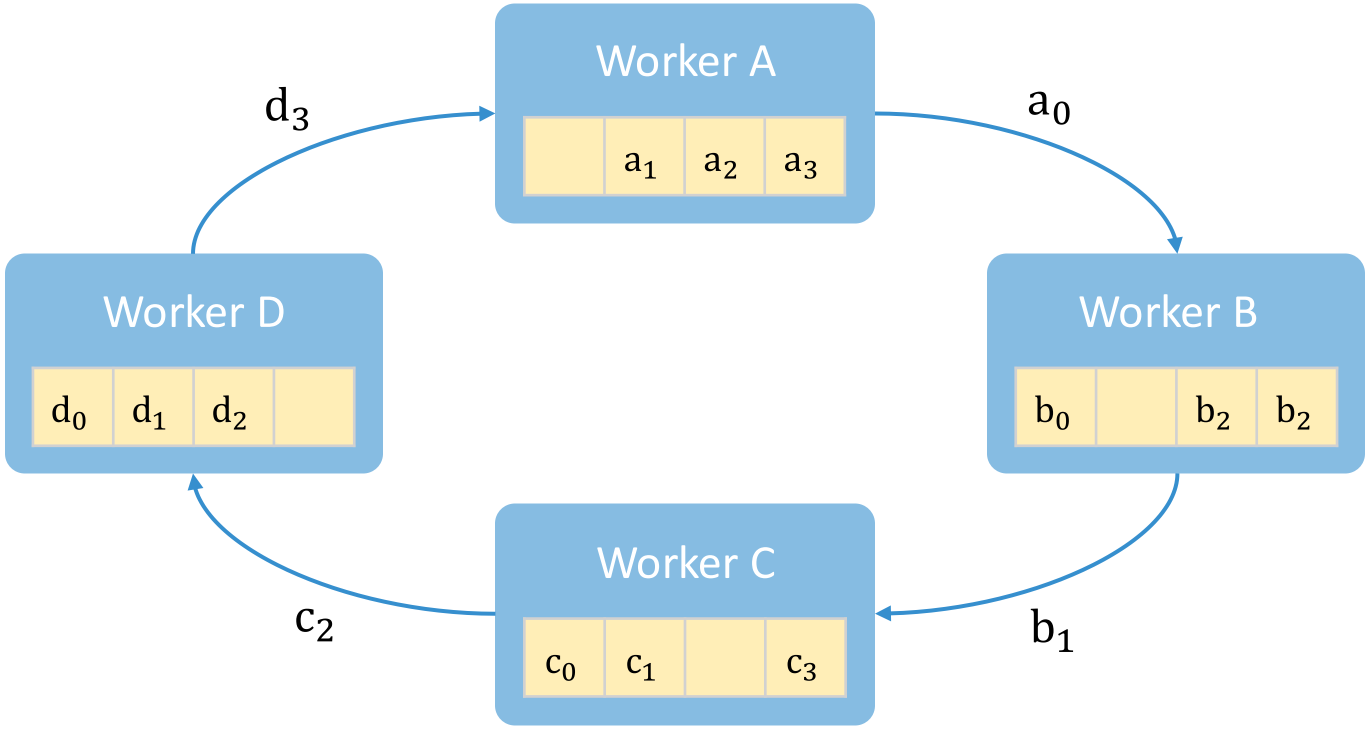

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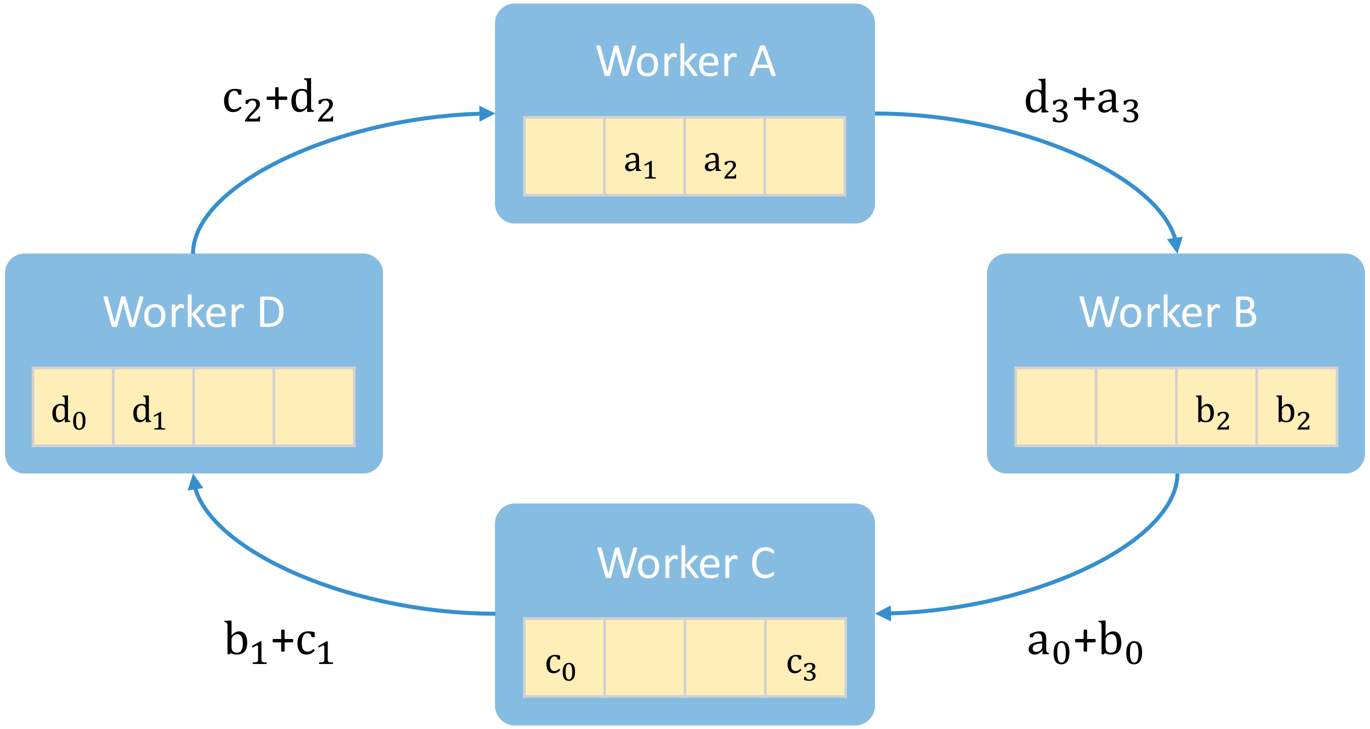
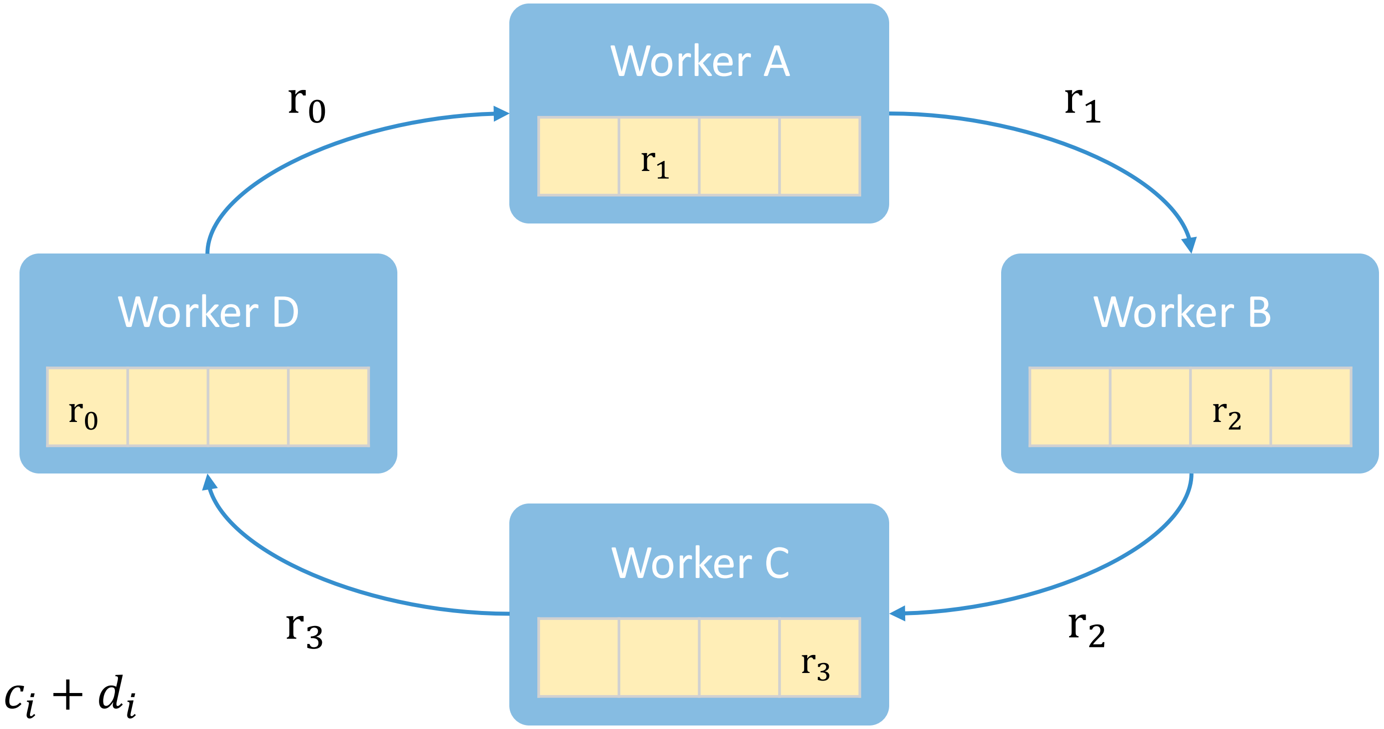


Ring All-Reduce

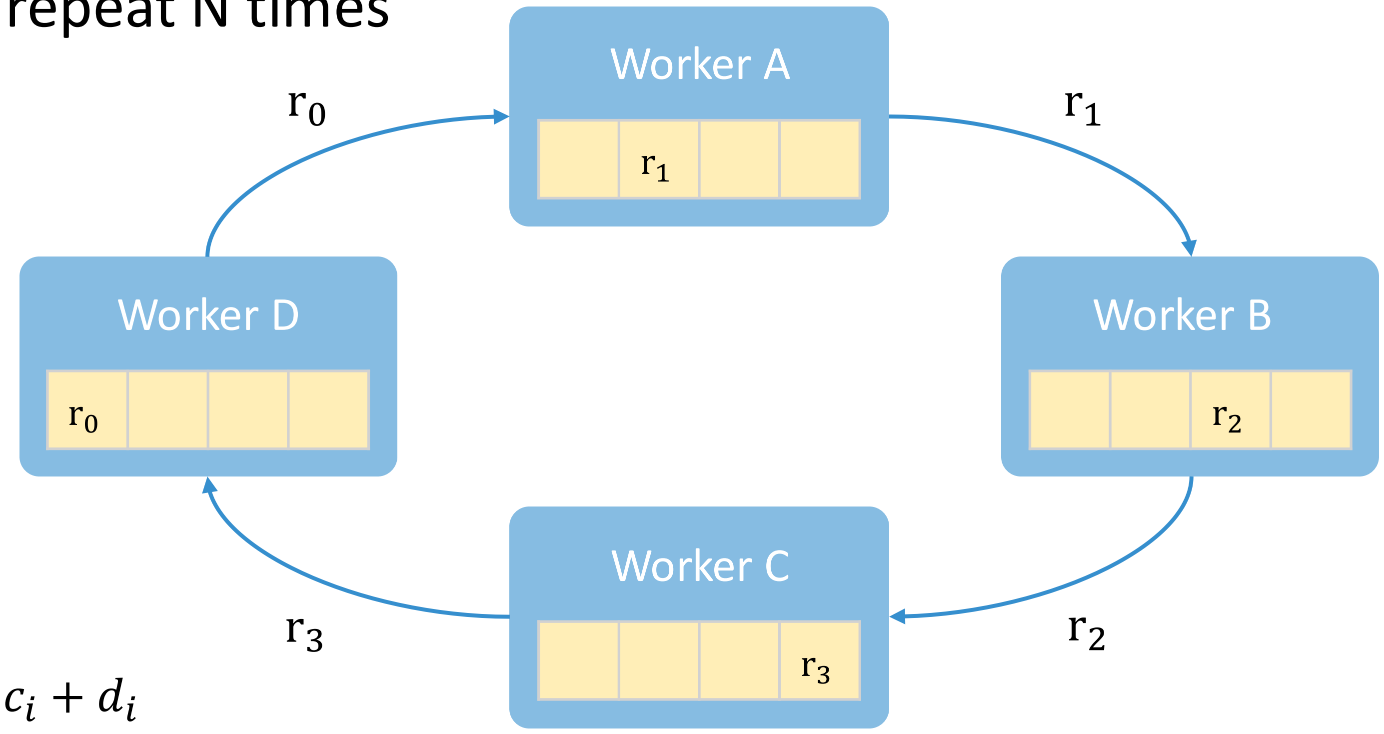
- Construct a ring of N workers, divide M parameters into N slices
- Step 1 (Aggregation): each worker send one slice (M/N parameters) to the next worker on the ring; repeat N times
- After step 1, each worker has the aggregated version of M/N parameters



$$r_i = a_i + b_i + c_i + d_i$$

Ring All-Reduce

- Construct a ring of N workers, divide M parameters into N slices
- Step 1 (Aggregation): each worker send one slice (M/N parameters) to the next worker on the ring; repeat N times
- Step 2 (Broadcast): each worker send one slice of aggregated parameters to the next worker; repeat N times



$r_i = a_i + b_i + c_i + d_i$

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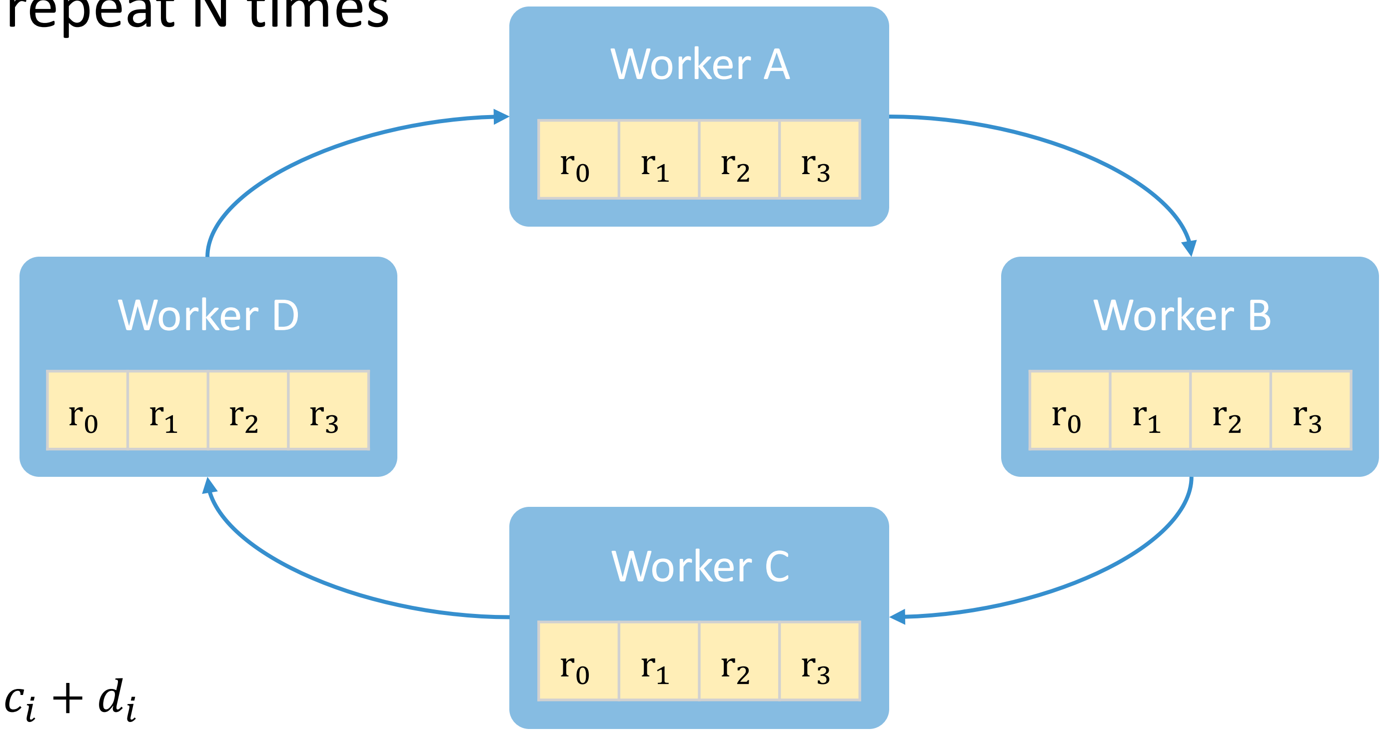

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Ring All-Reduce

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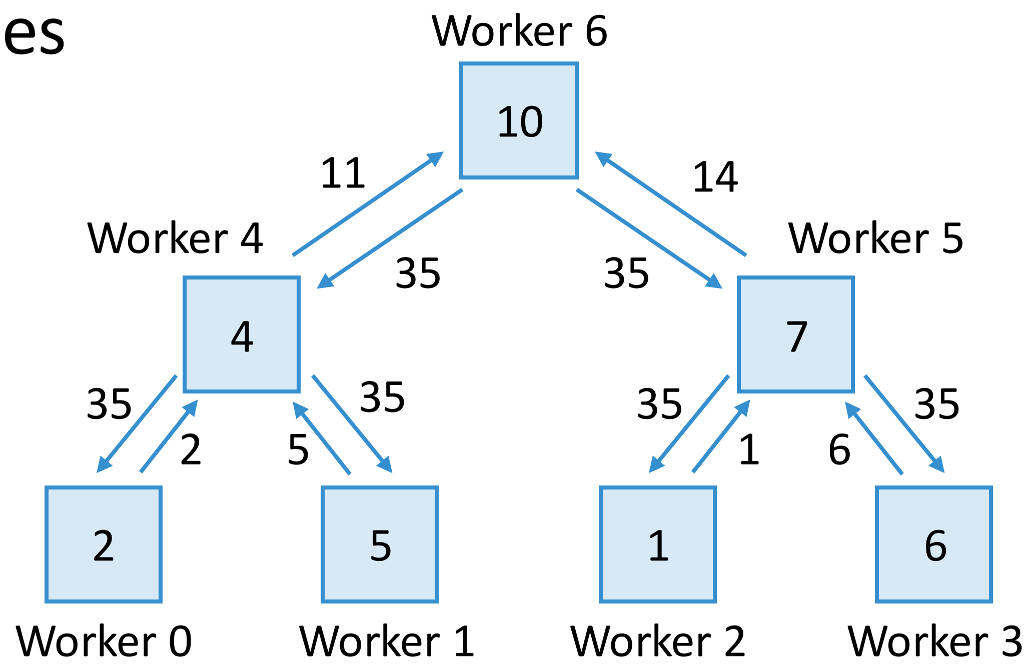
- Construct a ring of N workers, divide M parameters into N slices
- Step 1 (Aggregation): each worker send one slice (M/N parameters) to the next worker on the ring; repeat N times
- Step 2 (Broadcast): each worker send one slice of aggregated parameters to the next worker; repeat N times
- Overall communication: 2 * M * N parameters
  - Aggregation: M * N parameters
  - Broadcast: M * N parameters

Tree All-Reduce

- Construct a tree of N workers;
- Step 1 (Aggregation): each worker sends M parameters to its parent; repeat log(N) times
- Step 2 (Broadcast): each worker sends M parameters to its children; repeat log(N) times



Tree All-Reduce

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- Step 2 (Broadcast): each worker sends M parameters to its children; repeat log(N) times
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Butterfly Network

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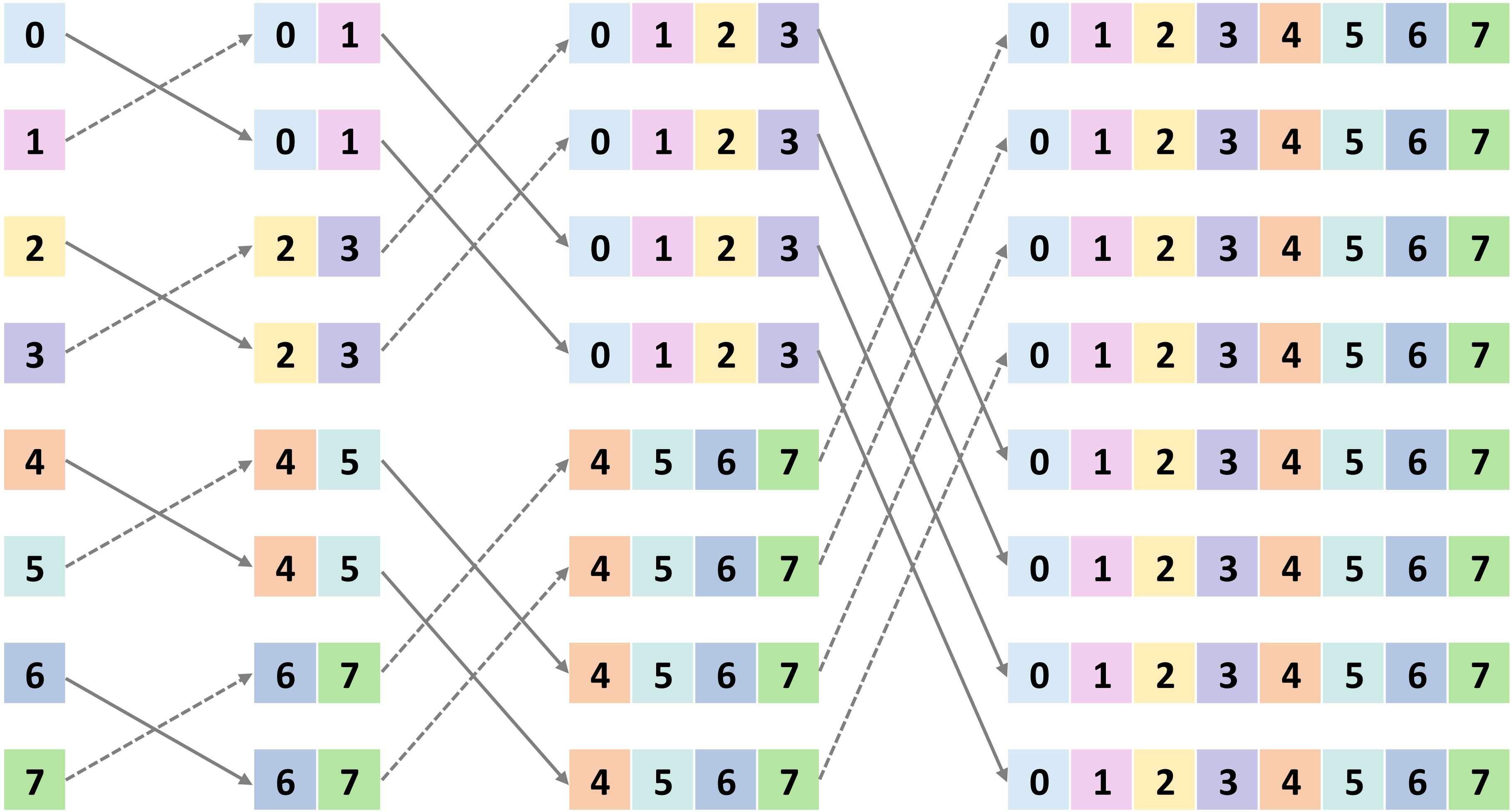

Butterfly All-Reduce

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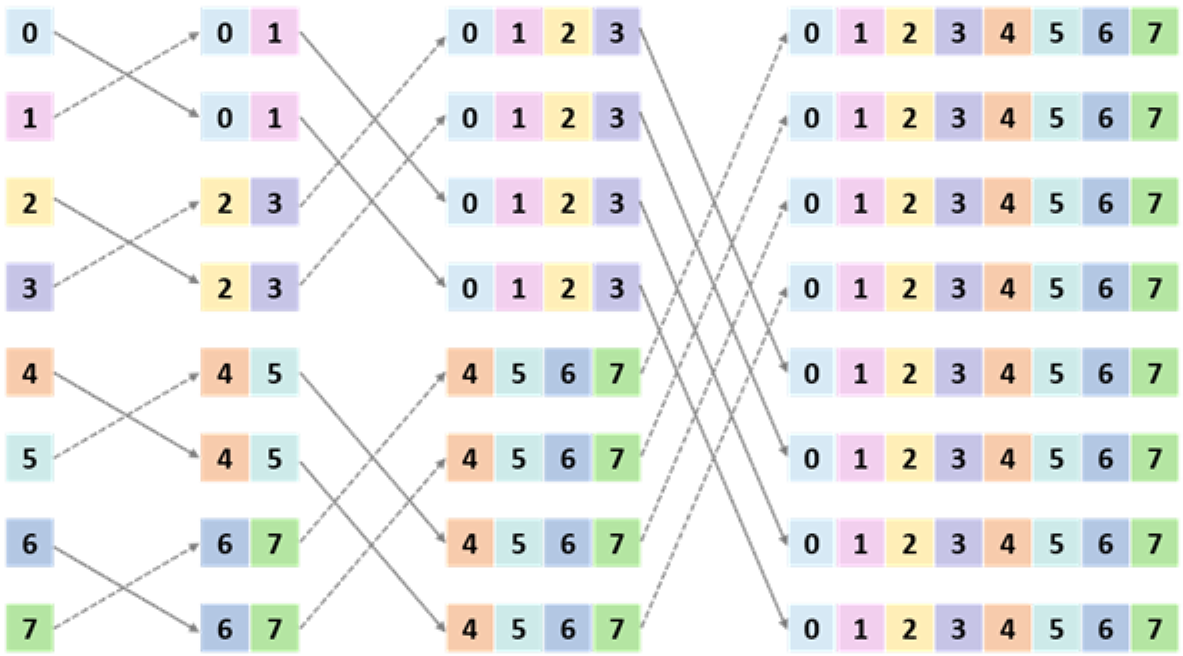
- Repeat log(N) times:

    1. Each worker sends M parameters to its target node in the butterfly network

    2. Each worker aggregates gradients locally

- Overall communication: N * M * log(N) parameters



Comparing different All-Reduce Methods

	Parameter Server	Naïve All-Reduce	Ring All-Reduce	Tree All-Reduce	Butterfly All-Reduce
Overall communication	$2 \times N \times M$	$N^2 \times M$	$2 \times N \times M$	$2 \times N \times M$	$N \times M \times \log N$

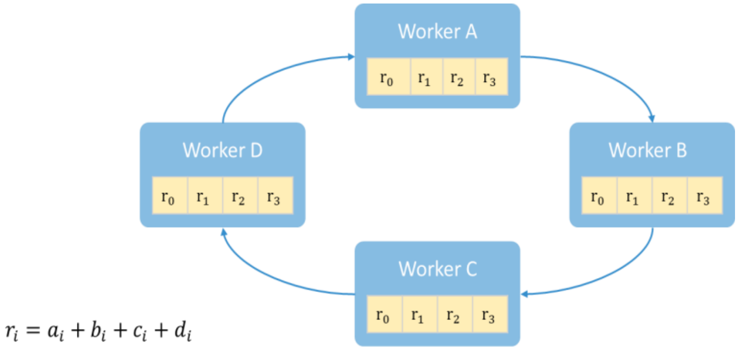
- Question: Ring All-Reduce is more efficient and scalable then Tree All-Reduce and Parameter Server, why?

Ring v.s. Tree v.s. Parameter Server

Ring All-Reduce:

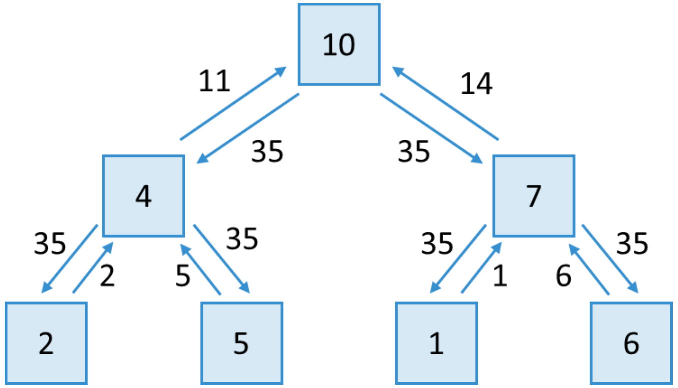
- Best latency
- Balanced workload across workers
- More scalable since each worker

sends 2*M parameters (independent to the number of workers)



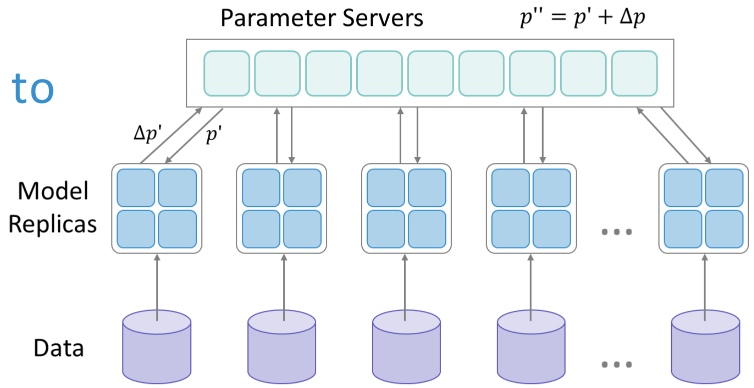
Each worker sends **M/N** parameters per iteration; repeat for **2*N** iterations

Latency: M/N * (2*N) / bandwidth



Each worker sends **M** parameters per iteration; repeat for **2*log(N)** iterations

Latency: M * 2 * log(N) / bandwidth

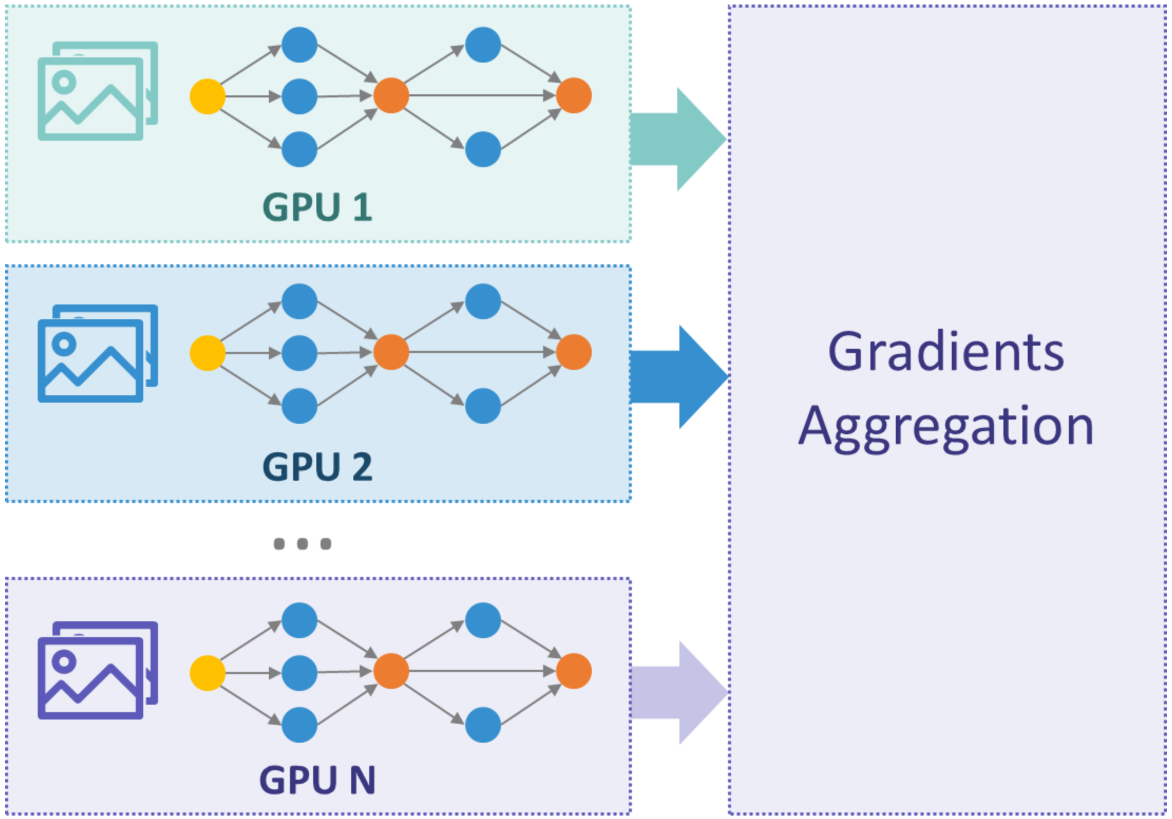


All workers send **M** parameters to parameter servers and receive **M** parameters from servers

Latency: M * N / bandwidth

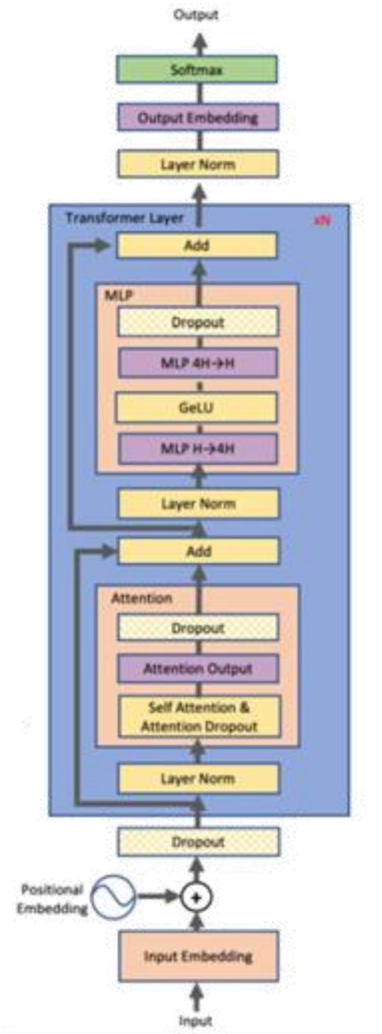
An Issue with Data Parallelism

- Each GPU saves a replica of the entire model
- Cannot train large models that exceed GPU device memory



Large Model Training Challenges

	BertLarge	GPT-2	Turing 17.2 NLG	GPT-3
Parameters	0.32B	1.5B	17.2B	175B
Layers	24	48	78	96
Hidden Dimension	1024	1600	4256	12288
Relative Computation	1x	4.7x	**54x**	**547x**
Memory Footprint	5.12GB	24GB	**275GB**	**2800GB**



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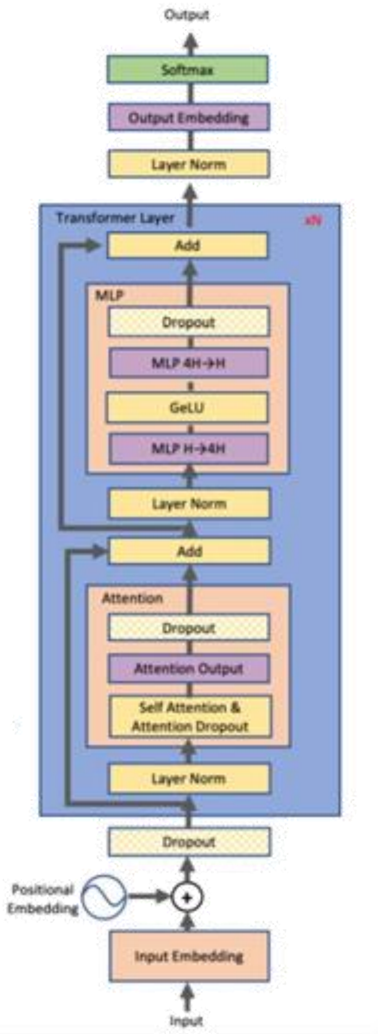
Out of Memory

NVIDIA V100 GPU memory capacity: 16G/32G
NVIDIA A100 GPU memory capacity: 40G/80G



ZeRO: Zero Redundancy Optimizer

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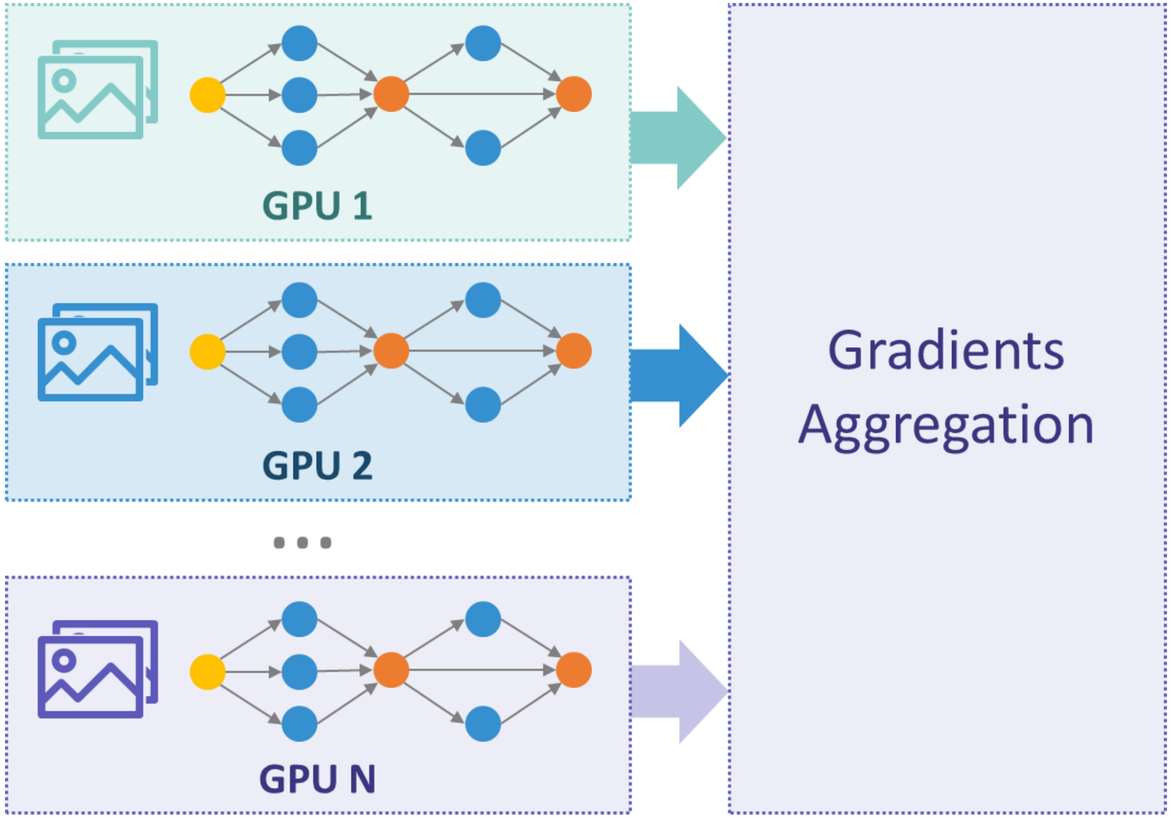
deepspeed

- Eliminating data redundancy in data parallel training
- A widely used technique for data parallel training of large models



Revisit: Stocastic Gradient Descent

For t = 1 to T

$$\Delta w = \eta \, x \frac{1}{b} \sum_{i=1}^{b} \underbrace{\nabla}_{\text{Backward pass}} \Big(\underbrace{loss\big(f_w(x_i, y_i)\big)}_{\text{Forward pass}} \Big)$$ // compute derivative and update

$\mathrm{w} \; -= \; \Delta \mathrm{w}$ // apply update

End

Adapted from Minjia Zhang, DeepSpeed Presentation

Adaptive Learning Rates (Adam)

For t = 1 to T

g = $\frac{1}{b}\sum_{i=1}^{b}\nabla\left(loss(f_w(x_i, y_i))\right)$

$\boxed{\Delta w = adam(g)}$

w -= Δw   // apply update

End

$$\nu_t = \beta_1 * \nu_{t-1} - (1-\beta_1) * g_t$$
$$s_t = \beta_2 * s_{t-1} - (1-\beta_2) * g_t^2$$
$$\Delta\omega_t = -\eta\frac{\nu_t}{\sqrt{s_t+\epsilon}} * g_t$$

g_t : *Gradient at time t along* ω^j

ν_t : *Exponential Average of gradients along* ω_j

s_t : *Exponential Average of squares of gradients along* ω_j

β_1, β_2 : *Hyperparameters*

[1] Kingma and Ba, "Adam: A Method for Stochastic Optimization", 2014, https://arxiv.org/abs/1412.6980

Understanding Memory Consumption

A 16-layer transformer model = 1 layer

Adapted from Minjia Zhang, DeepSpeed Presentation

Understanding Memory Consumption

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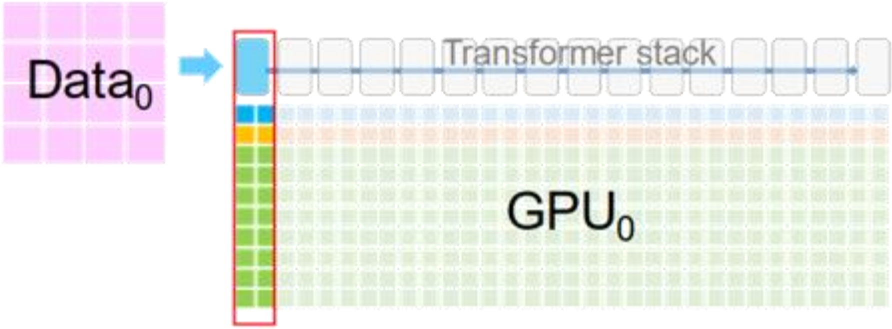

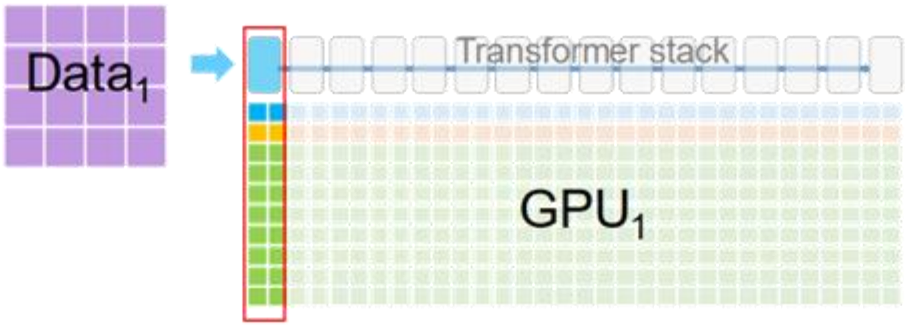

Each cell represents GPU memory used by its corresponding transformer layer

Adapted from Minjia Zhang, DeepSpeed Presentation

Understanding Memory Consumption

- FP16 parameter

Adapted from Minjia Zhang, DeepSpeed Presentation

Understanding Memory Consumption

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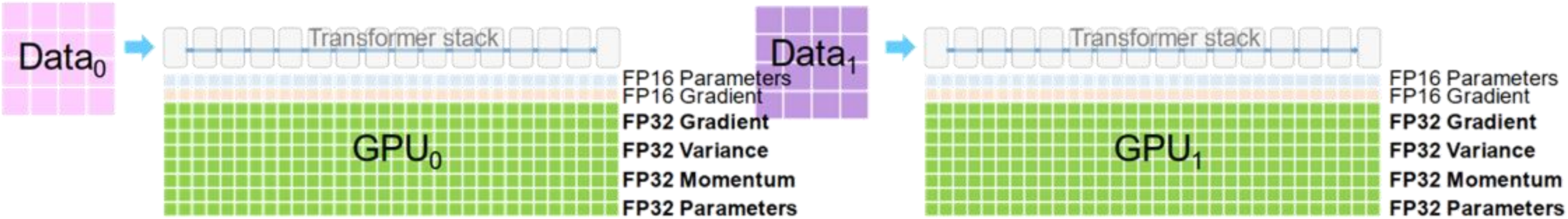
- FP16 parameter
- FP16 Gradients

Adapted from Minjia Zhang, DeepSpeed Presentation

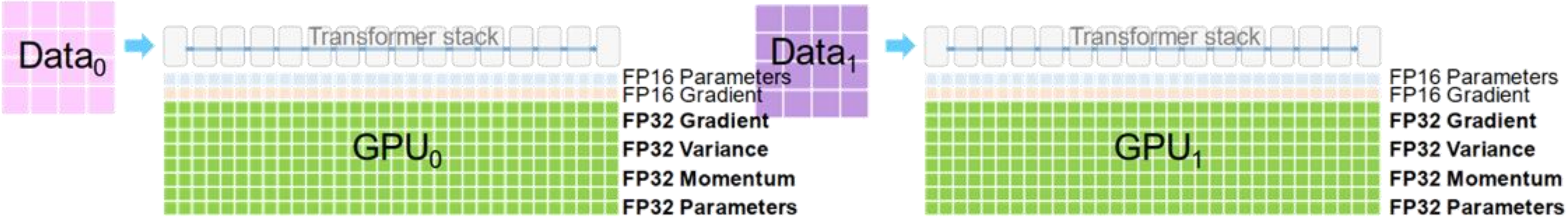
Understanding Memory Consumption



- FP16 parameter
- FP16 Gradients
- FP32 Optimizer States
  - Gradients, Variance, Momentum, Parameters

Adapted from Minjia Zhang, DeepSpeed Presentation

Understanding Memory Consumption



- FP16 parameter： **2M bytes**
- FP16 Gradients： **2M bytes**
- FP32 Optimizer States ： **16M bytes**
  - Gradients, Variance, Momentum, Parameters

M = number of parameters in the model

Example 1B parameter model -> 20GB/GPU

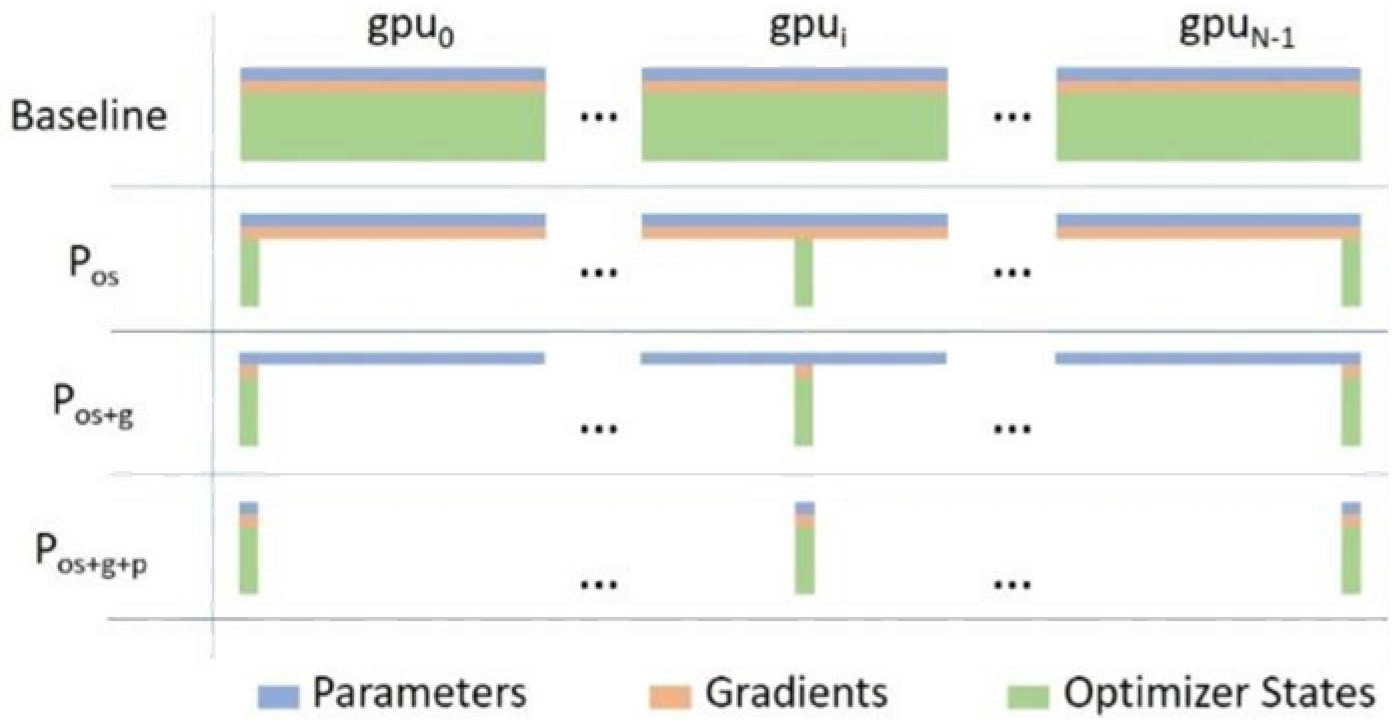
Memory consumption doesn't include:

- Input batch + activations

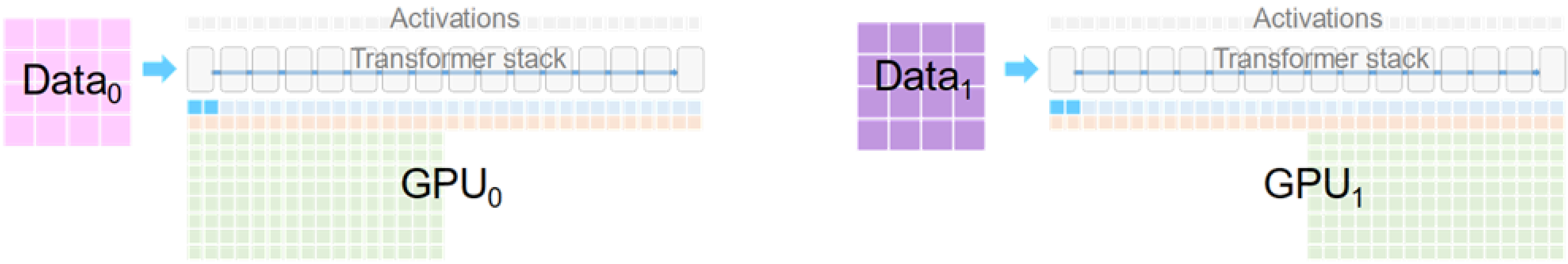
Adapted from Minjia Zhang, DeepSpeed Presentation

ZeRO-DP: ZeRO powered Data Parallelism

- ZeRO removes the redundancy across data parallel process
- Stage 1: partitioning optimizer states
- Stage 2: partitioning gradients
- Stage 3: partitioning parameters



ZeRO Stage 1: Partitioning Optimizer States



- ZeRO Stage 1
- Partitions optimizer states across GPUs

Adapted from Minjia Zhang, DeepSpeed Presentation

ZeRO Stage 1: Partitioning Optimizer States

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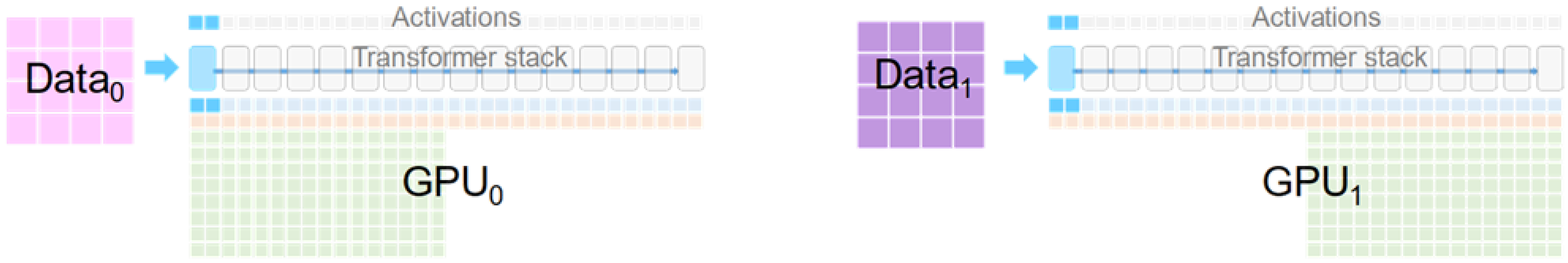

- ZeRO Stage 1
- Partitions optimizer states across GPUs
- Run Forward across the transformer blocks

Adapted from Minjia Zhang, DeepSpeed Presentation

ZeRO Stage 1: Partitioning Optimizer States

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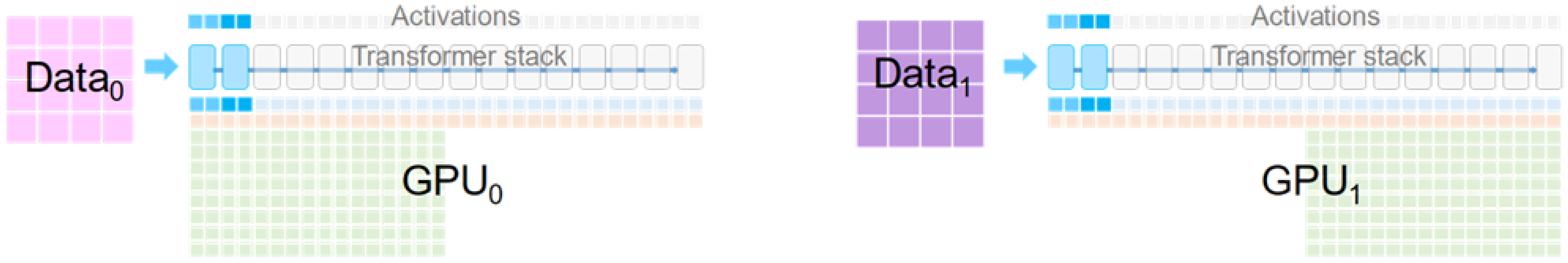

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Adapted from Minjia Zhang, DeepSpeed Presentation

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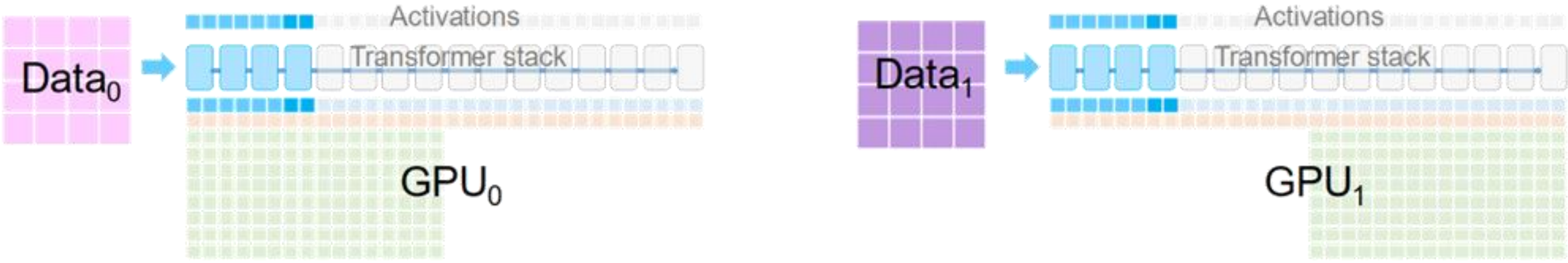

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Adapted from Minjia Zhang, DeepSpeed Presentation

ZeRO Stage 1: Partitioning Optimizer States

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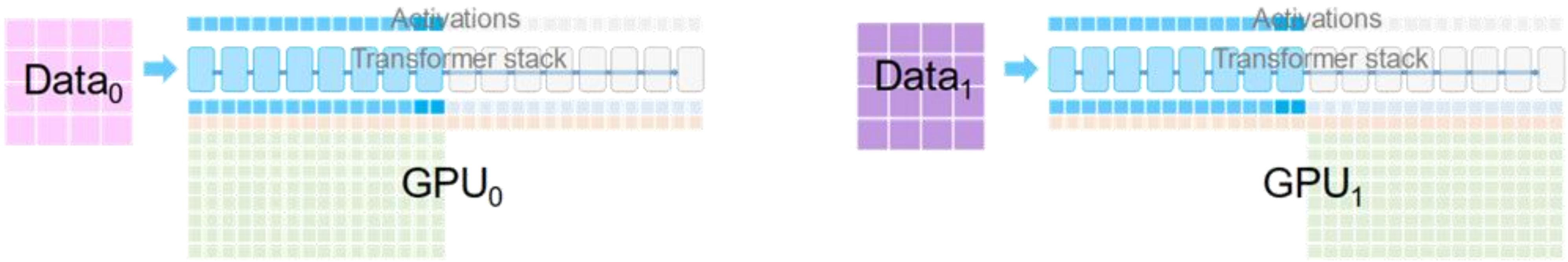

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Adapted from Minjia Zhang, DeepSpeed Presentation

ZeRO Stage 1: Partitioning Optimizer States

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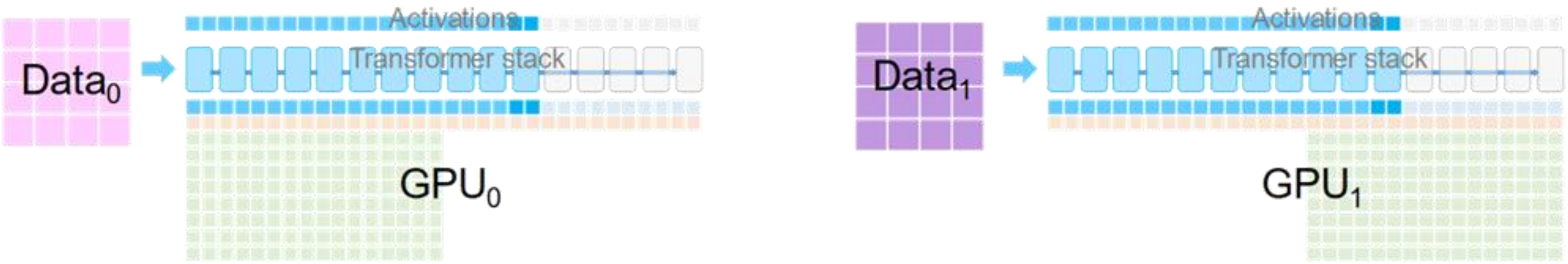

- ZeRO Stage 1
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Adapted from Minjia Zhang, DeepSpeed Presentation

ZeRO Stage 1: Partitioning Optimizer States

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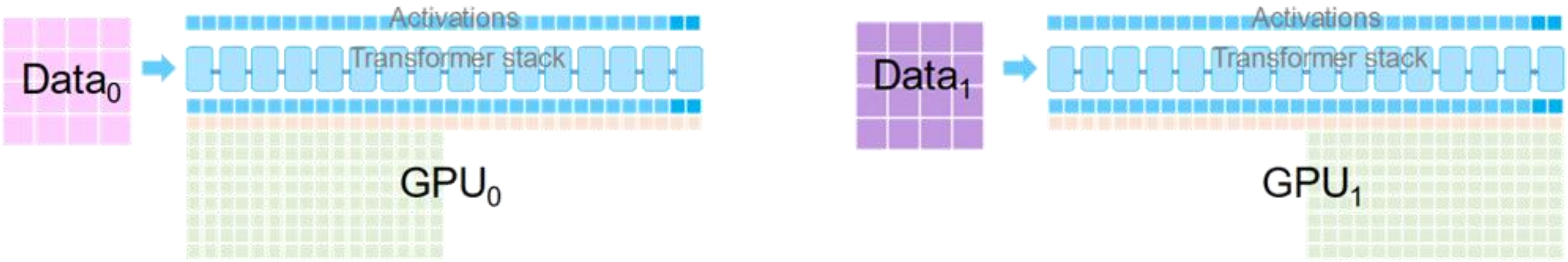

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Adapted from Minjia Zhang, DeepSpeed Presentation

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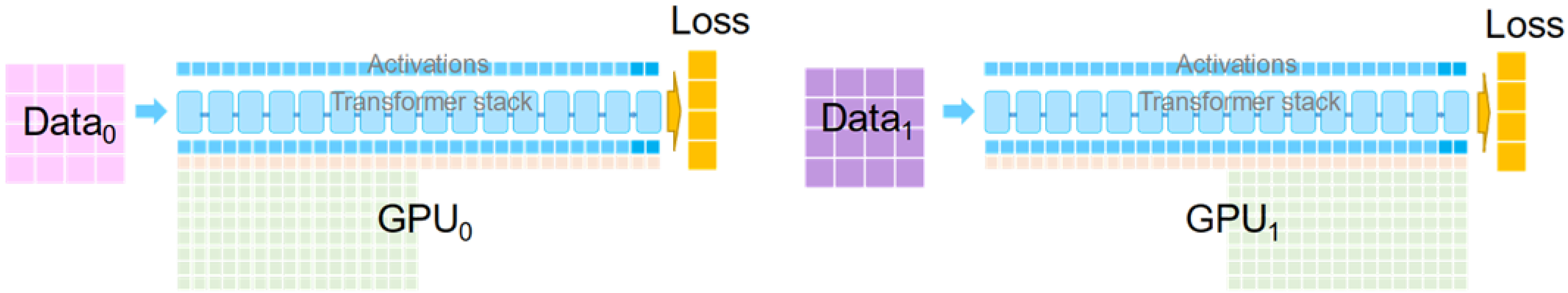

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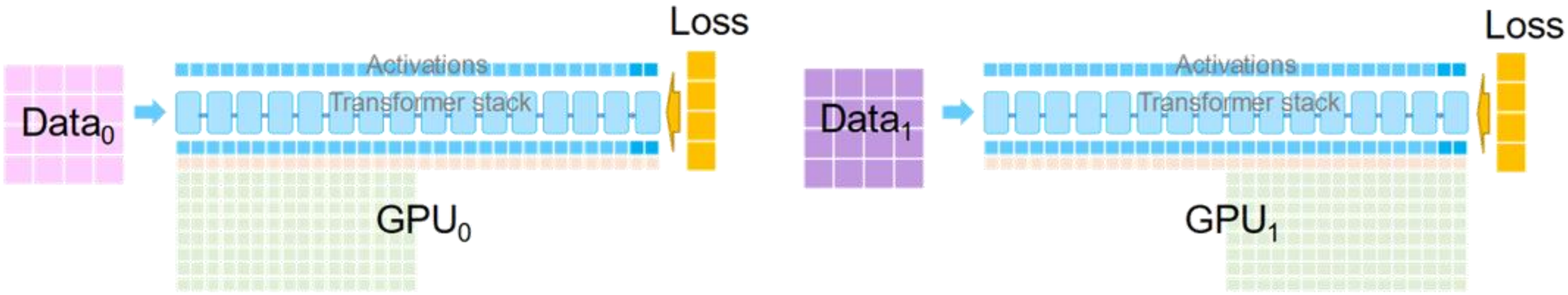
Adapted from Minjia Zhang, DeepSpeed Presentation

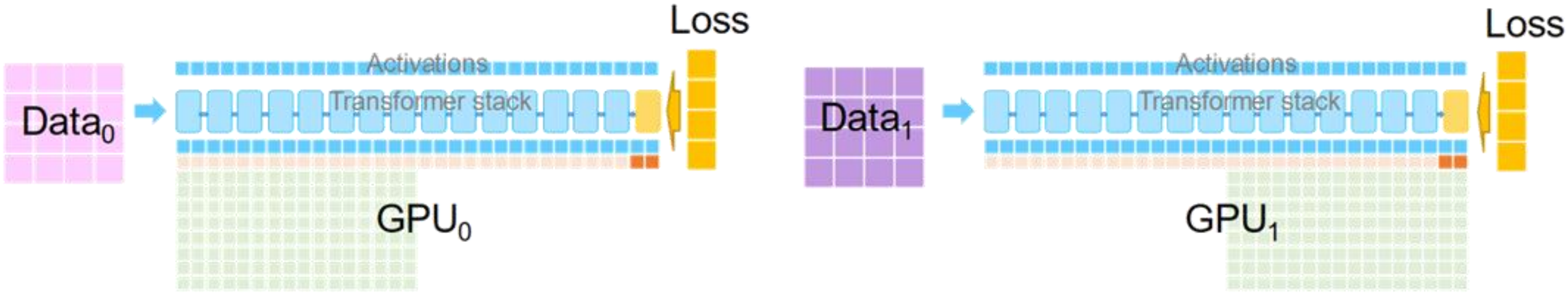
ZeRO Stage 1: Partitioning Optimizer States



- ZeRO Stage 1
- Partitions optimizer states across GPUs
- Run Forward across the transformer blocks
- Backward propagation to generate FP16 gradients

Adapted from Minjia Zhang, DeepSpeed Presentation

ZeRO Stage 1: Partitioning Optimizer States



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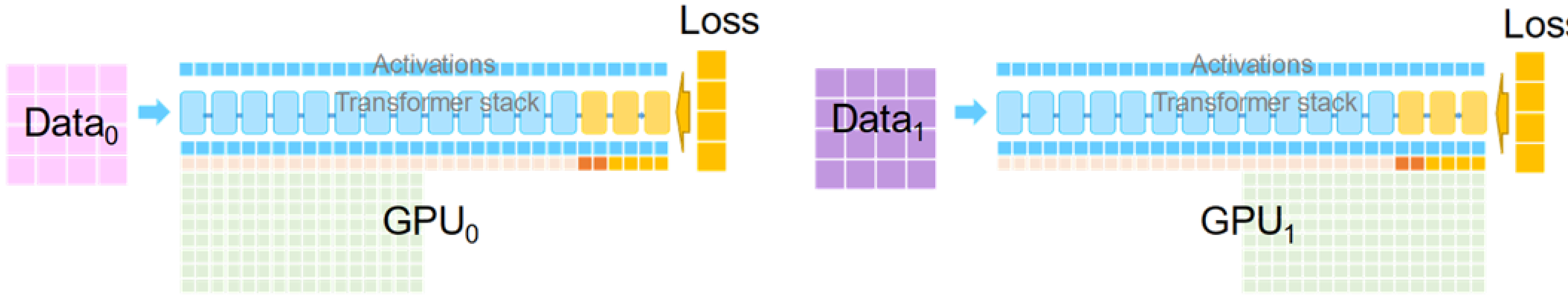
Adapted from Minjia Zhang, DeepSpeed Presentation

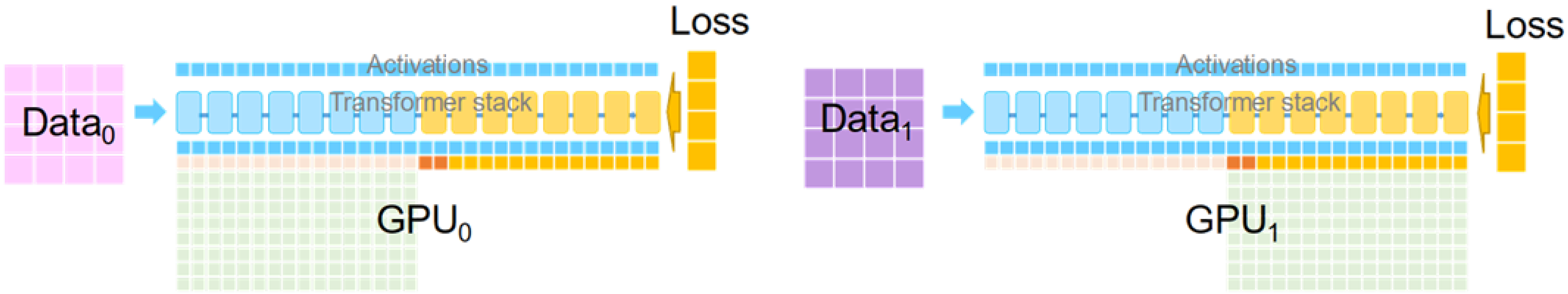
ZeRO Stage 1: Partitioning Optimizer States



- ZeRO Stage 1
- Partitions optimizer states across GPUs
- Run Forward across the transformer blocks
- Backward propagation to generate FP16 gradients

Adapted from Minjia Zhang, DeepSpeed Presentation

ZeRO Stage 1: Partitioning Optimizer States



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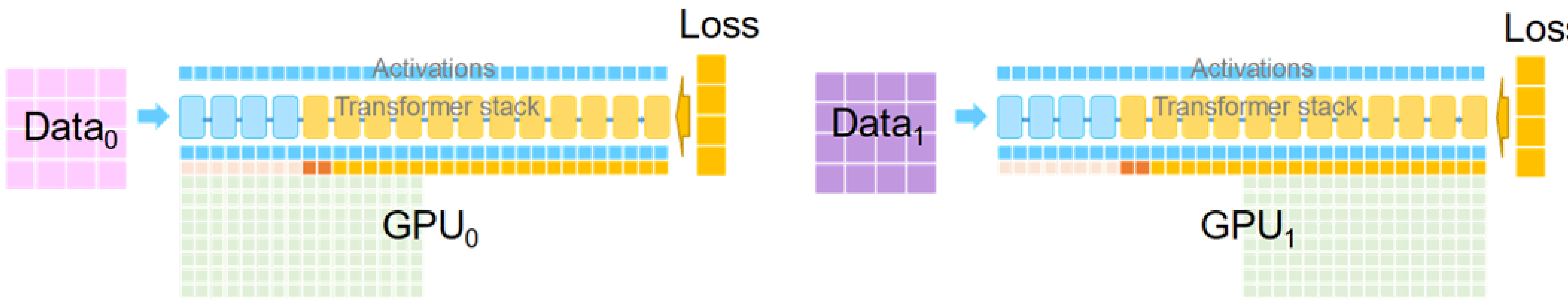

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ZeRO Stage 1: Partitioning Optimizer States

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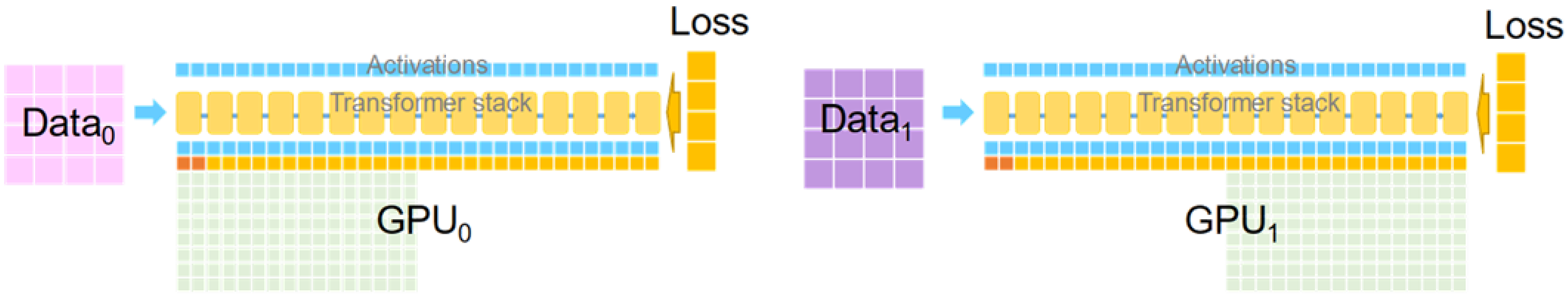

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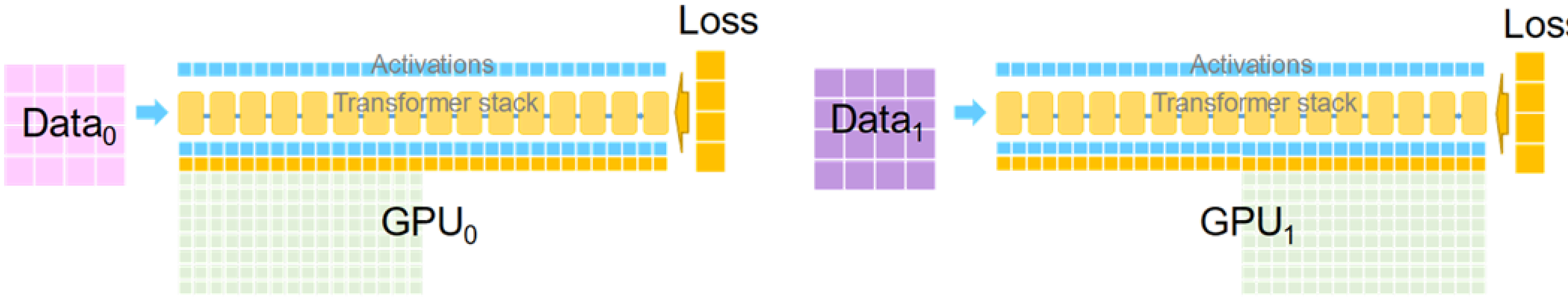

- ZeRO Stage 1
- Partitions optimizer states across GPUs
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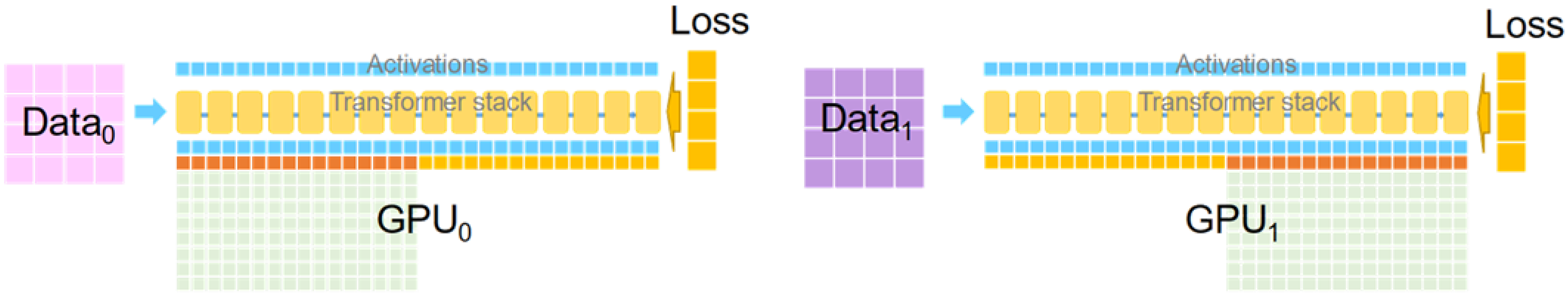
Adapted from Minjia Zhang, DeepSpeed Presentation

ZeRO Stage 1: Partitioning Optimizer States



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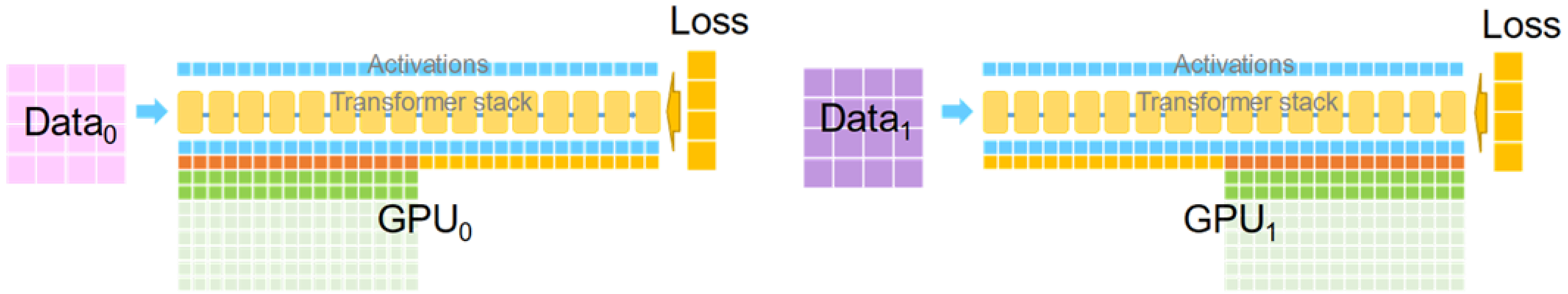

- ZeRO Stage 1
- Partitions optimizer states across GPUs
- Run Forward across the transformer blocks
- Backward propagation to generate FP16 gradients and All-Reduce to average
- Update the FP32 weights with ADAM optimizer

Adapted from Minjia Zhang, DeepSpeed Presentation

ZeRO Stage 1: Partitioning Optimizer States

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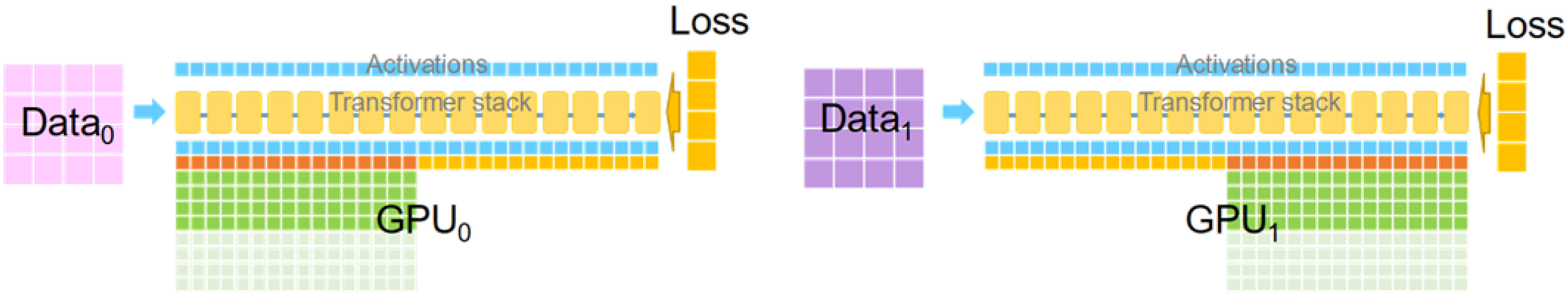

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ZeRO Stage 1: Partitioning Optimizer States

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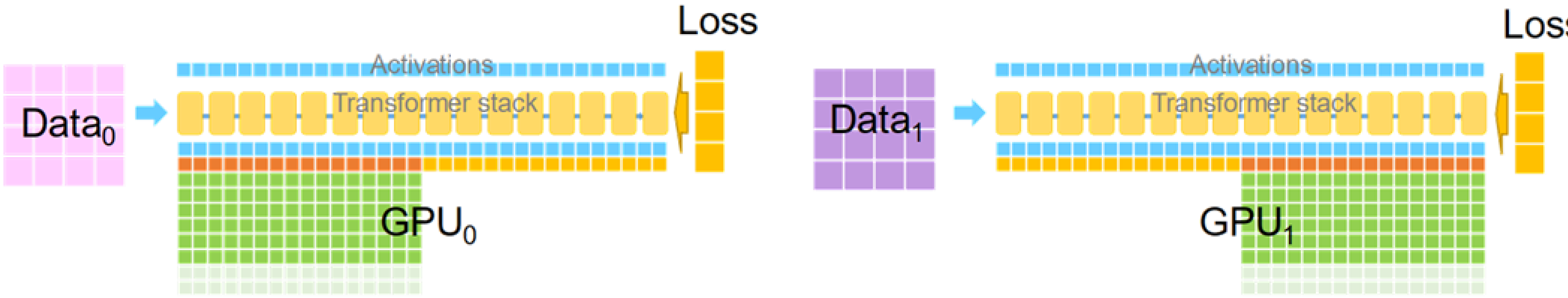

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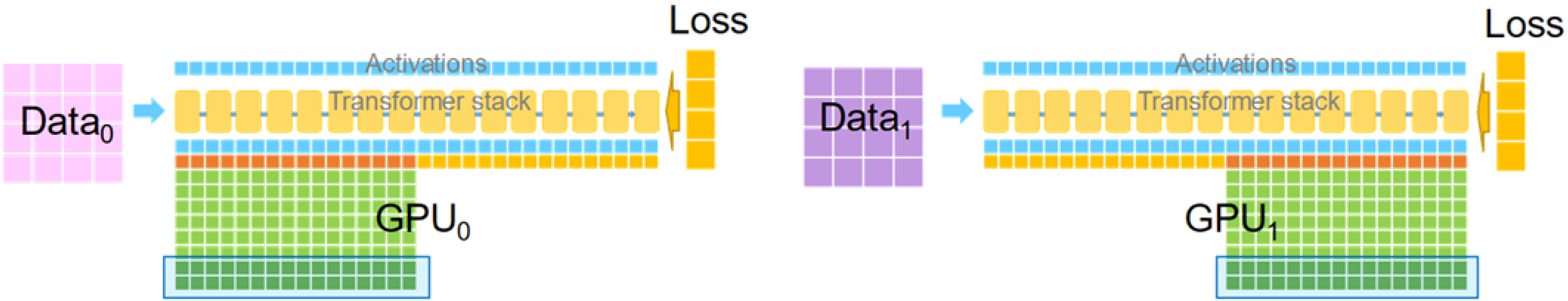
ZeRO Stage 1: Partitioning Optimizer States



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ZeRO Stage 1: Partitioning Optimizer States

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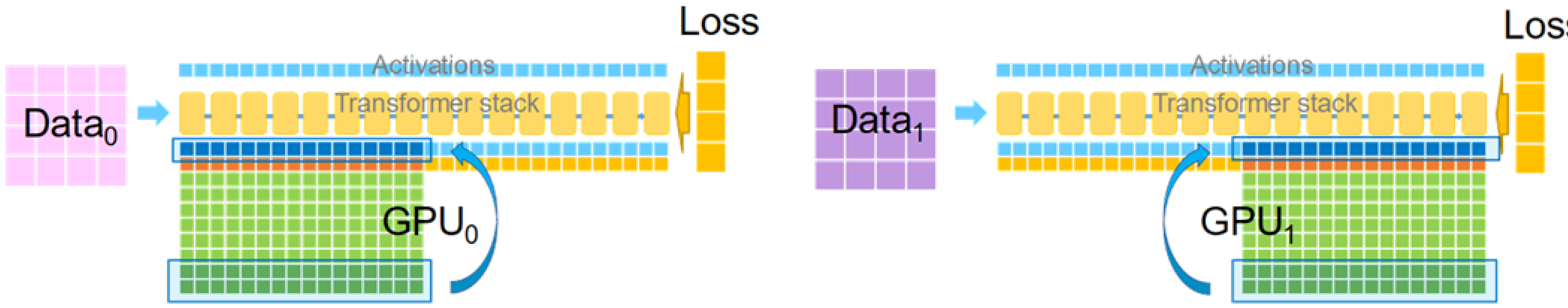

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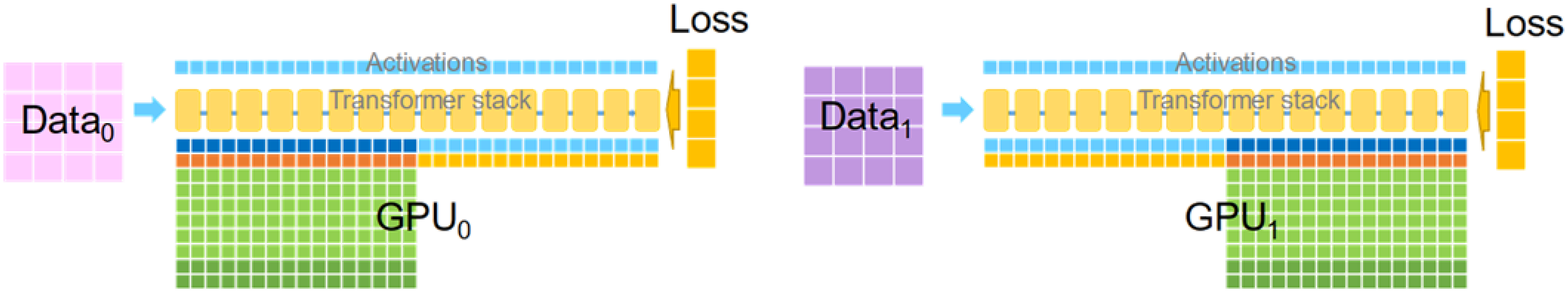

- ZeRO Stage 1
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-

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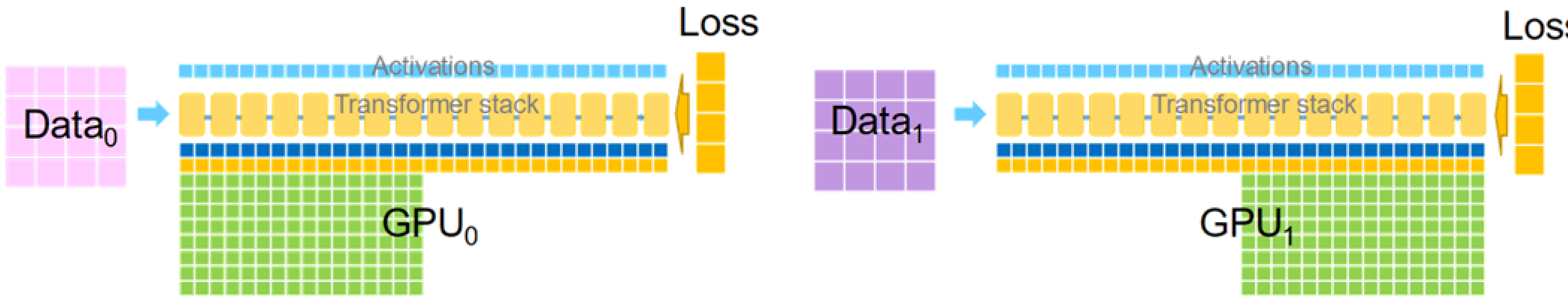
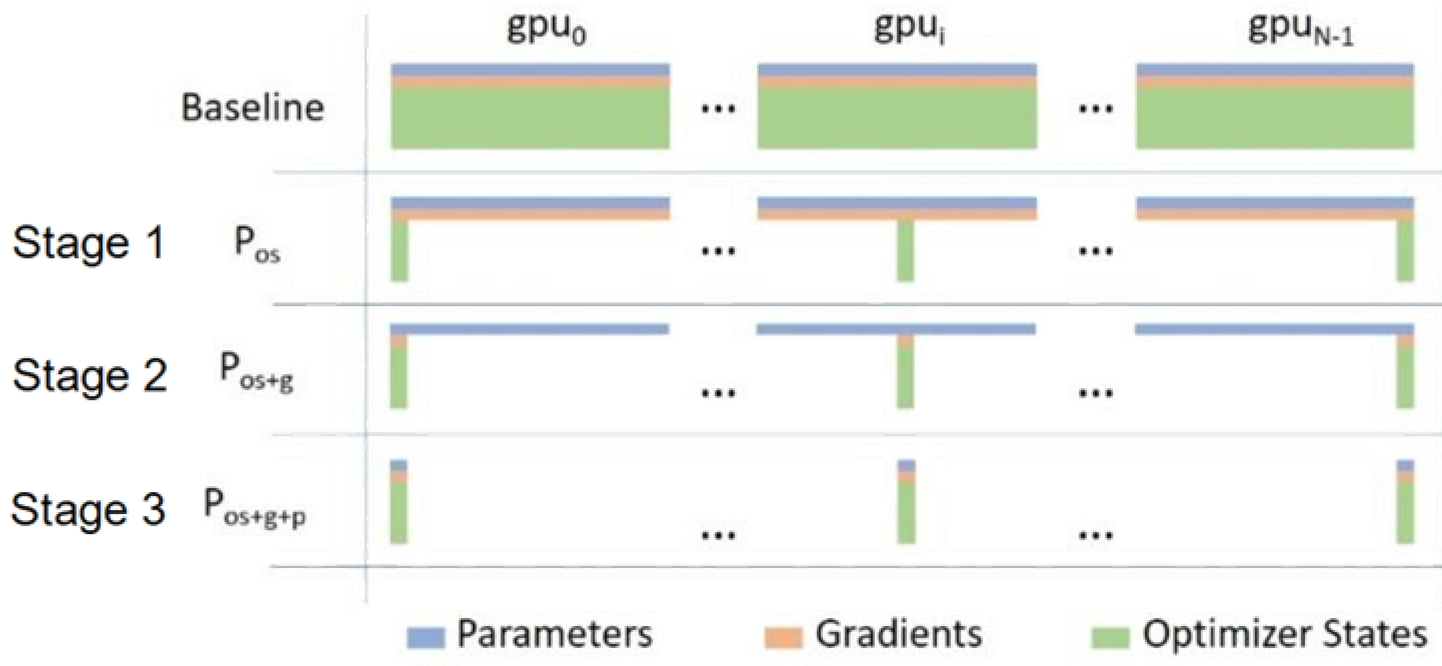


- ZeRO Stage 1
- Partitions optimizer states across GPUs
- Run Forward across the transformer blocks
- Backward propagation to generate FP16 gradients and All-Reduce to average
- Update the FP32 weights with ADAM optimizer
- Update the FP16 weights
- All Gather the FP16 weights to complete the iteration

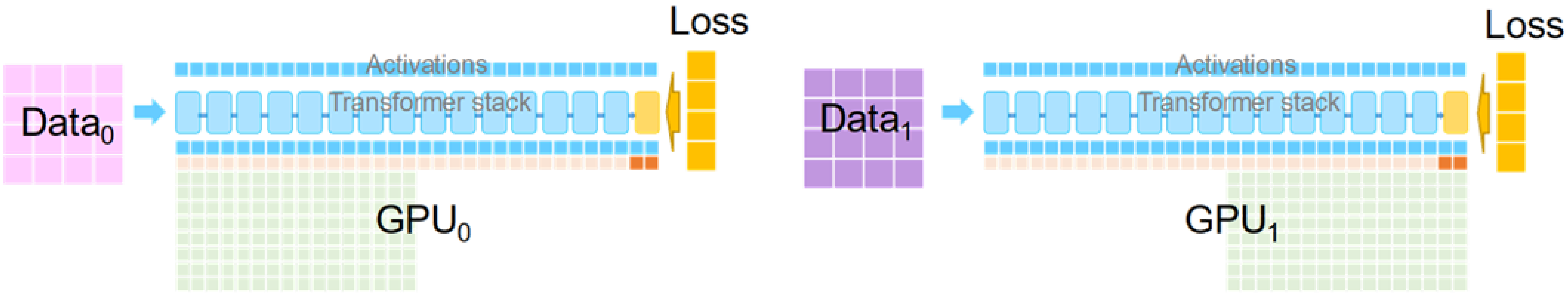
ZeRO: Zero Redundancy Optimizer

- Progressive memory savings and communication volume



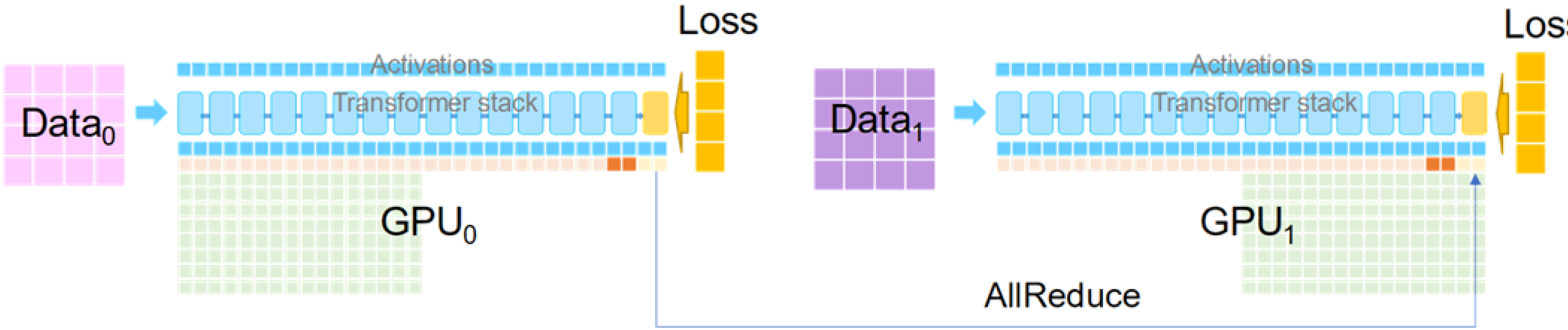
	Memory Consumption		Comm Volume
	Formulation	Specific Example $K=12$ $\Psi=7.5B$ $N_d=64$	
Baseline	$(2+2+K)*\Psi$	120GB	1x
Stage 1 P_{os}	$2\Psi+2\Psi+\frac{K*\Psi}{N_d}$	31.4GB	1x
Stage 2 P_{os+g}	$2\Psi+\frac{(2+K)*\Psi}{N_d}$	16.6GB	1x
Stage 3 P_{os+g+p}	$\frac{(2+2+K)*\Psi}{N_d}$	1.9GB	1.5x

ZeRO Stage 2: Partitioning Gradients



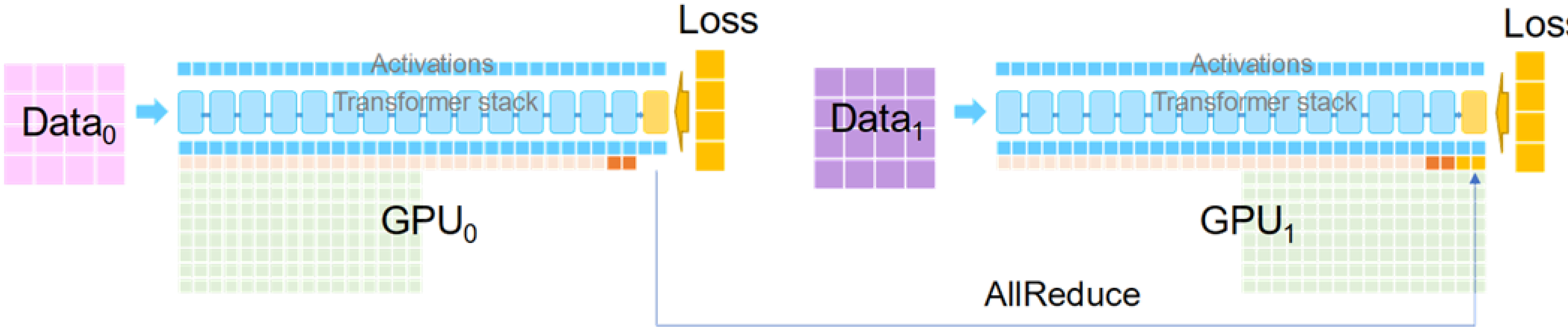
- Partitioning gradients across GPUs
- The forward process remains the same as stage 1

ZeRO Stage 2: Partitioning Gradients



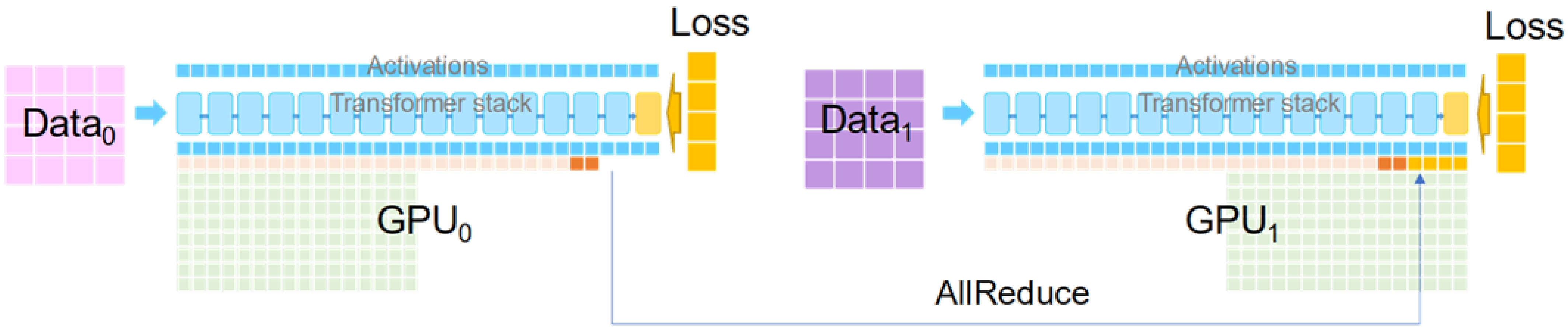
- Partitioning gradients across GPUs
- Perform All-Reduce right after back propagation of each layer

ZeRO Stage 2: Partitioning Gradients



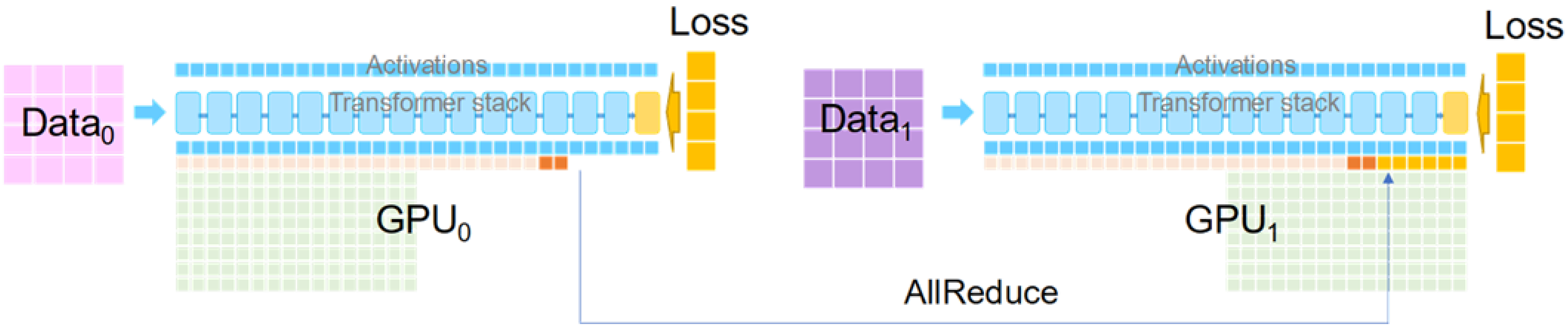
- Partitioning gradients across GPUs
- Only one GPU keeps the gradients after All-Reduce

ZeRO Stage 2: Partitioning Gradients



- Partitioning gradients across GPUs
- Reduce gradients on GPUs responsible for updating parameters

ZeRO Stage 2: Partitioning Gradients



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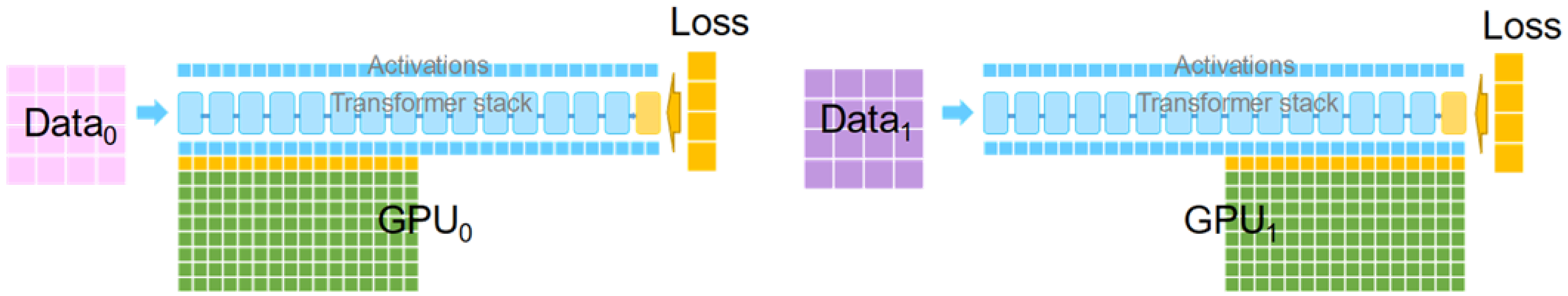
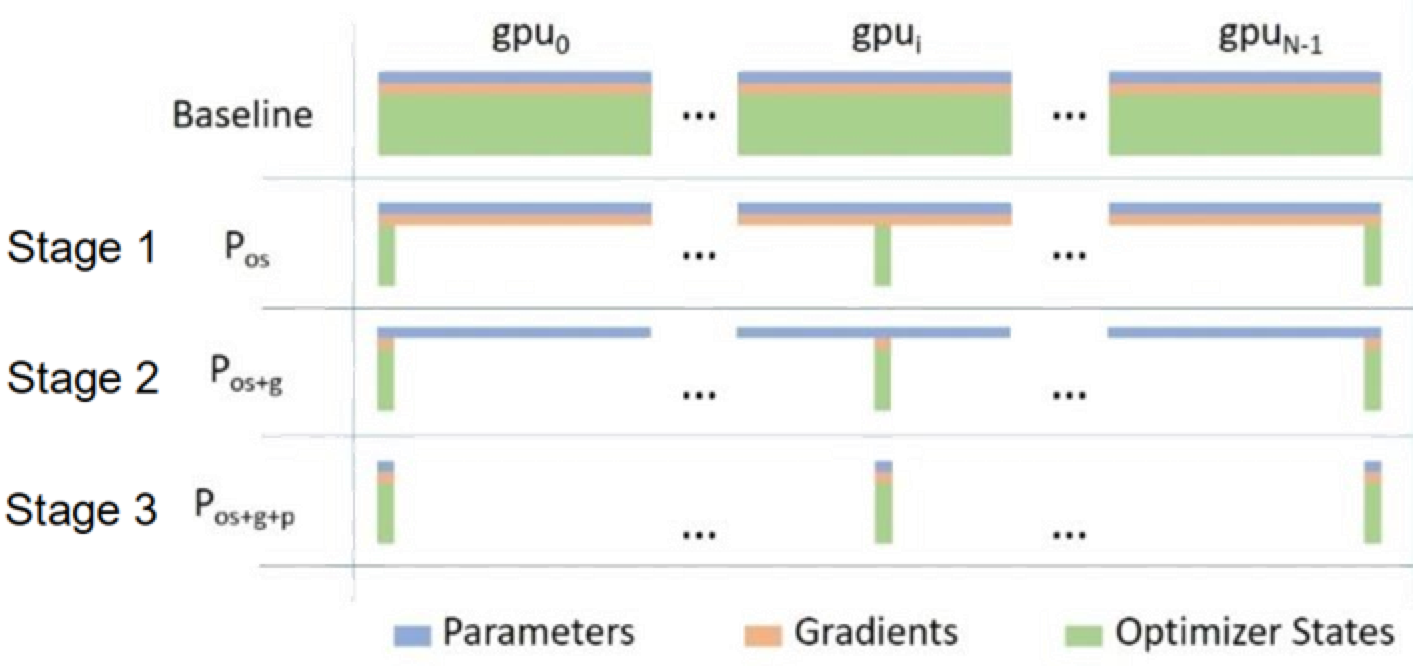


- Partitioning gradients across GPUs
- Reduce gradients on GPUs responsible for updating parameters

ZeRO: Zero Redundancy Optimizer

- Progressive memory savings and communication volume
- Turning NLR 17.2B is powered by Stage 1 and Megatron



	Memory Consumption: Formulation	Memory Consumption: Specific Example (K=12 Ψ=7.5B N_d=64)	Comm Volume
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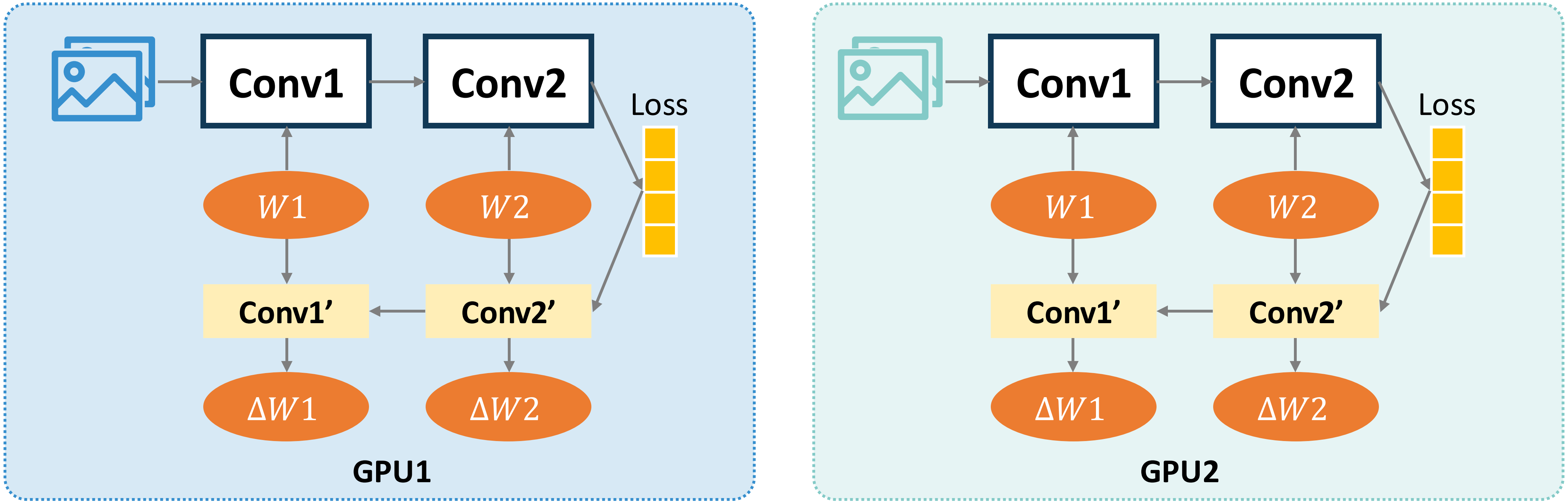
ZeRO Stage 3: Partitioning Parameters

- In data parallel training, all GPUs keep **all** parameters during training



ZeRO Stage 3: Partitioning Parameters

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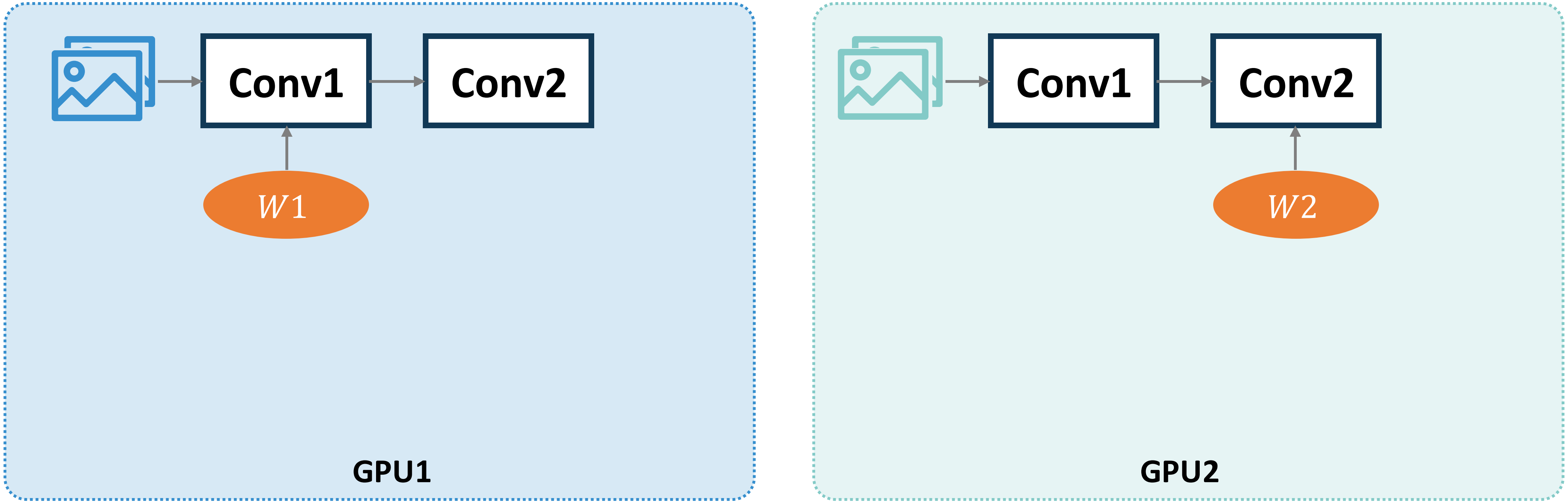
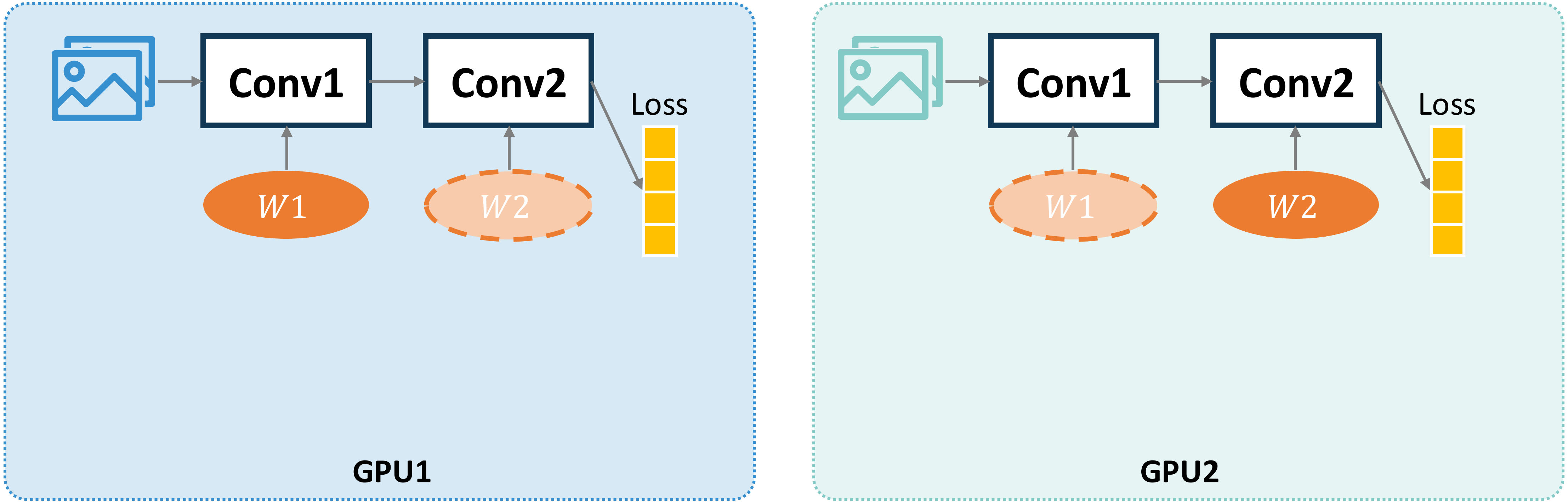
- In ZeRO, model parameters are partitioned across GPUs



ZeRO Stage 3: Partitioning Parameters

- In ZeRO, model parameters are partitioned across GPUs
- GPUs broadcast their parameters during forward



ZeRO Stage 3: Partitioning Parameters

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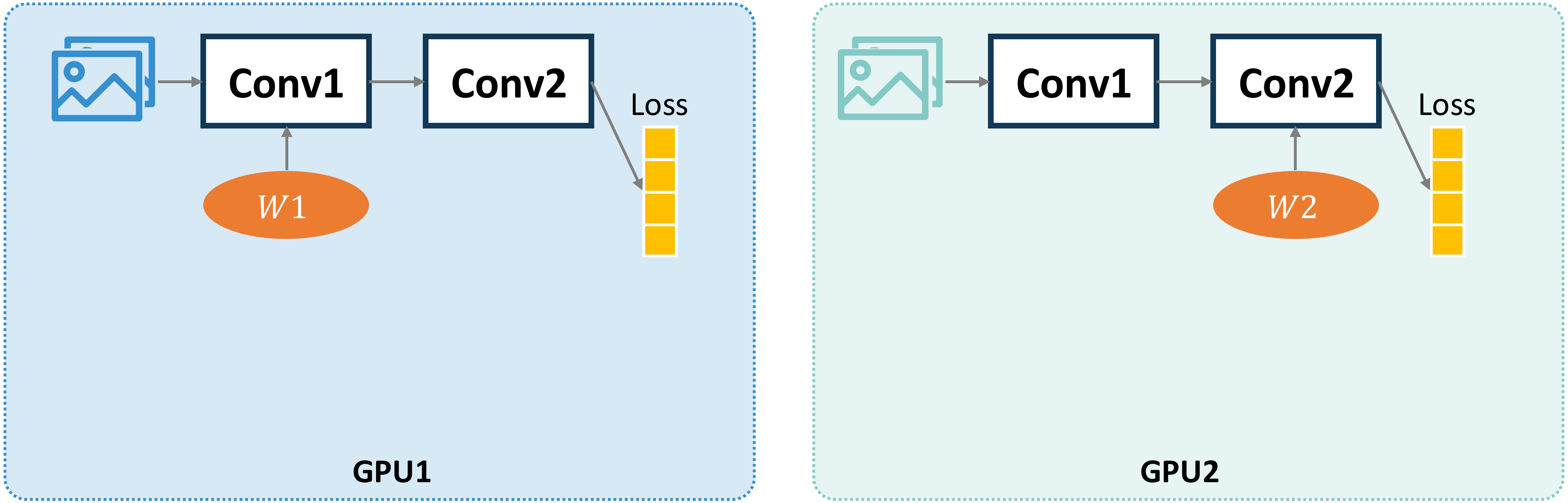
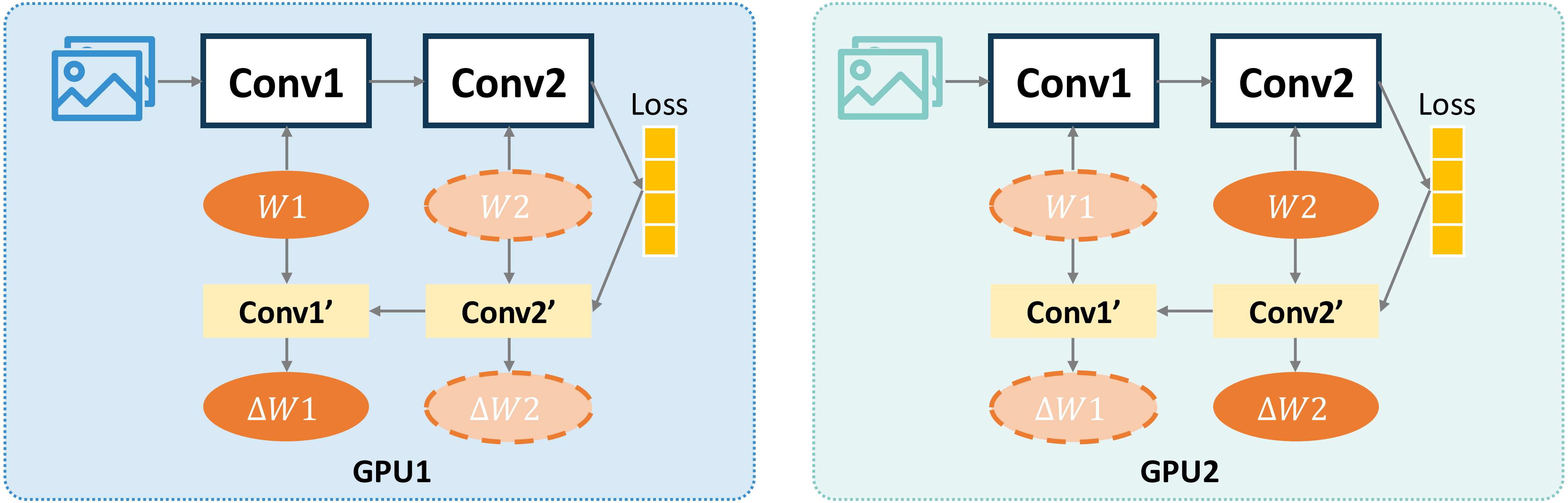
- In ZeRO, model parameters are partitioned across GPUs
- Parameters are discarded right after use



ZeRO Stage 3: Partitioning Parameters

- In ZeRO, model parameters are partitioned across GPUs
- GPUs broadcast their parameters again during backward



ZeRO: Zero Redundancy Optimizer

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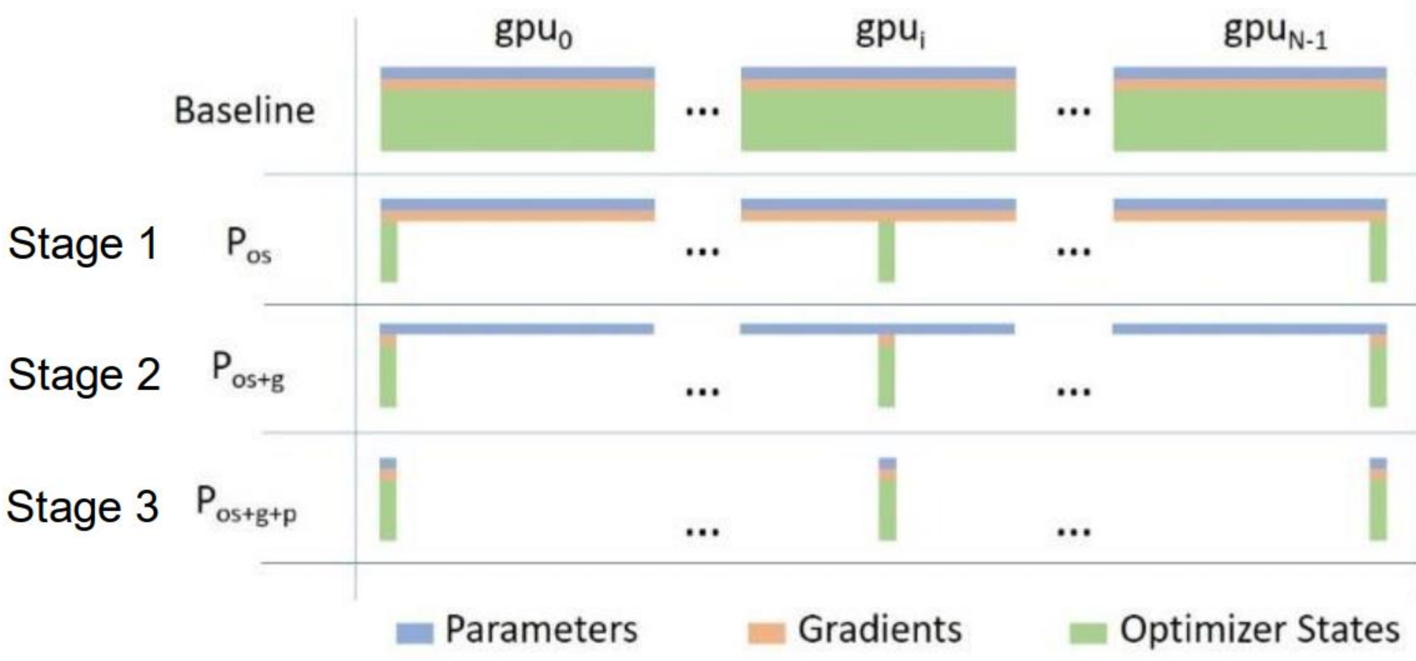
- ZeRO has three different stages
- Progressive memory savings and communication volume



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Acknowledgement

The development of this course, including its structure, content, and accompanying presentation slides, has been significantly influenced and inspired by the excellent work of instructors and institutions who have shared their materials openly. We wish to extend our sincere acknowledgement and gratitude to the following courses, which served as invaluable references and a source of pedagogical inspiration:

- Machine Learning Systems[15-442/15-642], by **Tianqi Chen** and **Zhihao Jia** at **CMU**.
- Advanced Topics in Machine Learning (Systems)[CS6216], by **Yao Lu** at **NUS**

While these materials provided a foundational blueprint and a wealth of insightful examples, all content herein has been adapted, modified, and curated to meet the specific learning objectives of our curriculum. Any errors, omissions, or shortcomings found in these course materials are entirely our own responsibility. We are profoundly grateful for the contributions of the educators listed above, whose dedication to teaching and knowledge-sharing has made the creation of this course possible.

System for Artificial Intelligence

Thanks

Siyuan Feng
Shanghai Innovation Institute