



Georgia Tech School of Electrical and Computer Engineering
College of Engineering



<http://synergy.ece.gatech.edu>



ASPLOS Tutorial

February 28, 2022

Enabling HW/SW Co-Design of Distributed Deep Learning Training Platforms

ASTRA-sim Tutorial



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Welcome



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Collaborators



Sudarshan Srinivasan

Research Scientist, Intel

Agenda

Time (CET)	Time (ET)	Topic	Presenter
15:00 – 16:00	9:00 – 10:00	Introduction to Distributed Deep Learning Training Platforms	Tushar Krishna
16:00 – 17:00	10:00 – 11:00	ASTRA-sim	Saeed Rashidi
17:00 – 17:10	11:00 – 11:10	Break	
17:10 – 17:50	11:10 – 11:50	Demo and Exercises	William Won and Taekyung Heo
17:50 – 18:00	11:50 – 12:00	Extensions and Future Development	Tushar Krishna and Saeed Rashidi

Tutorial Website

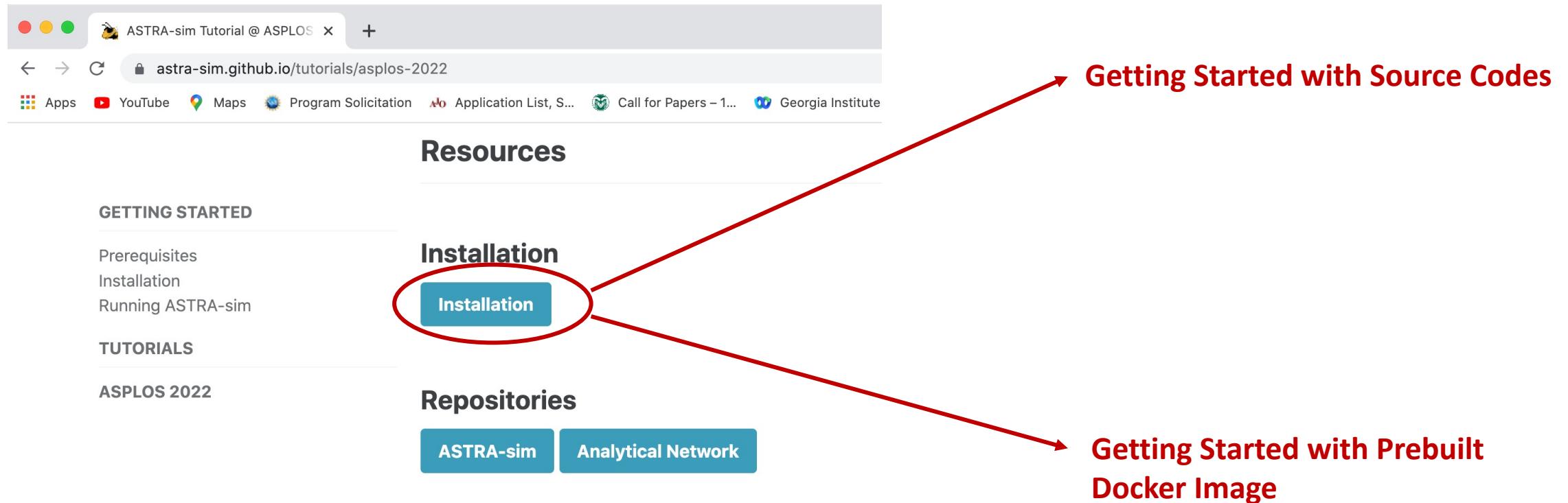
includes agenda, slides, ASTRA-sim installation instructions (via source + docker image)

<https://astra-sim.github.io/tutorials/asipos-2022>

Attention: Tutorial is being recorded

ASTRA-sim Installation

- Please go ahead and install ASTRA-sim!
- Instructions here:



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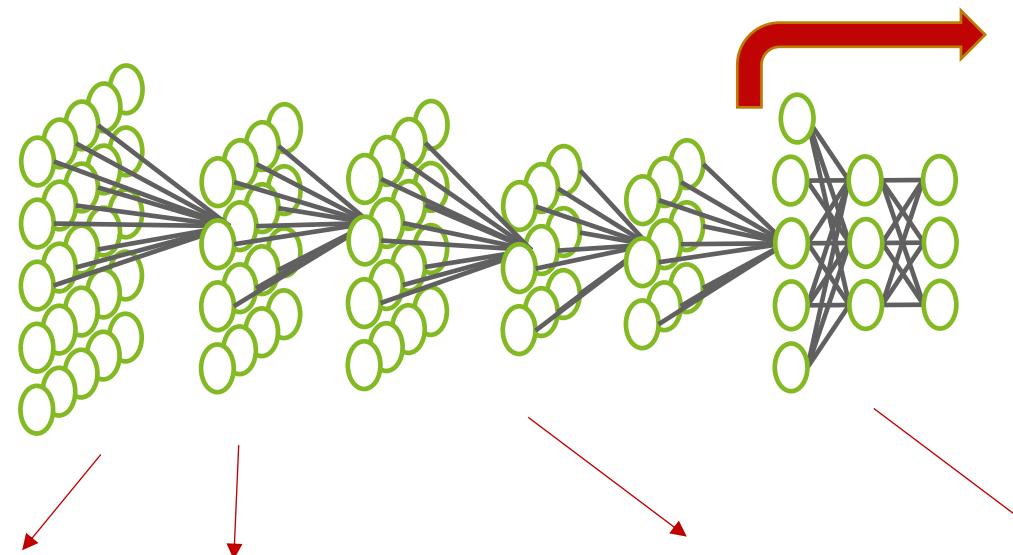
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The engine driving the AI Revolution



Training

Training a deep neural network (DNN) involves feeding it a training dataset to update its weights to model the underlying function representing the dataset



Object Detection



Speech Recognition



Language
Understanding



Recommender Systems

“Training” in the context of ML

- Machine Learning algorithms learn to make decisions or predictions based on data.
- We can categorize current ML algorithms based on the following three characteristics
 - **Feedback from data**
 - Supervised learning
 - Unsupervised learning
 - Semi-supervised learning
 - Reinforcement learning
 - **Purpose / Task**
 - Anomaly Detection
 - Classification
 - Clustering
 - Dimensionality Reduction
 - Representation Learning
 - Regression
 - **Method (for hyperparameter optimization)**
 - SGD
 - EA
 - Rule-based
 - Topic Models
 - ..

*We focus on Supervised Learning with SGD
--> most popular for DNNs*

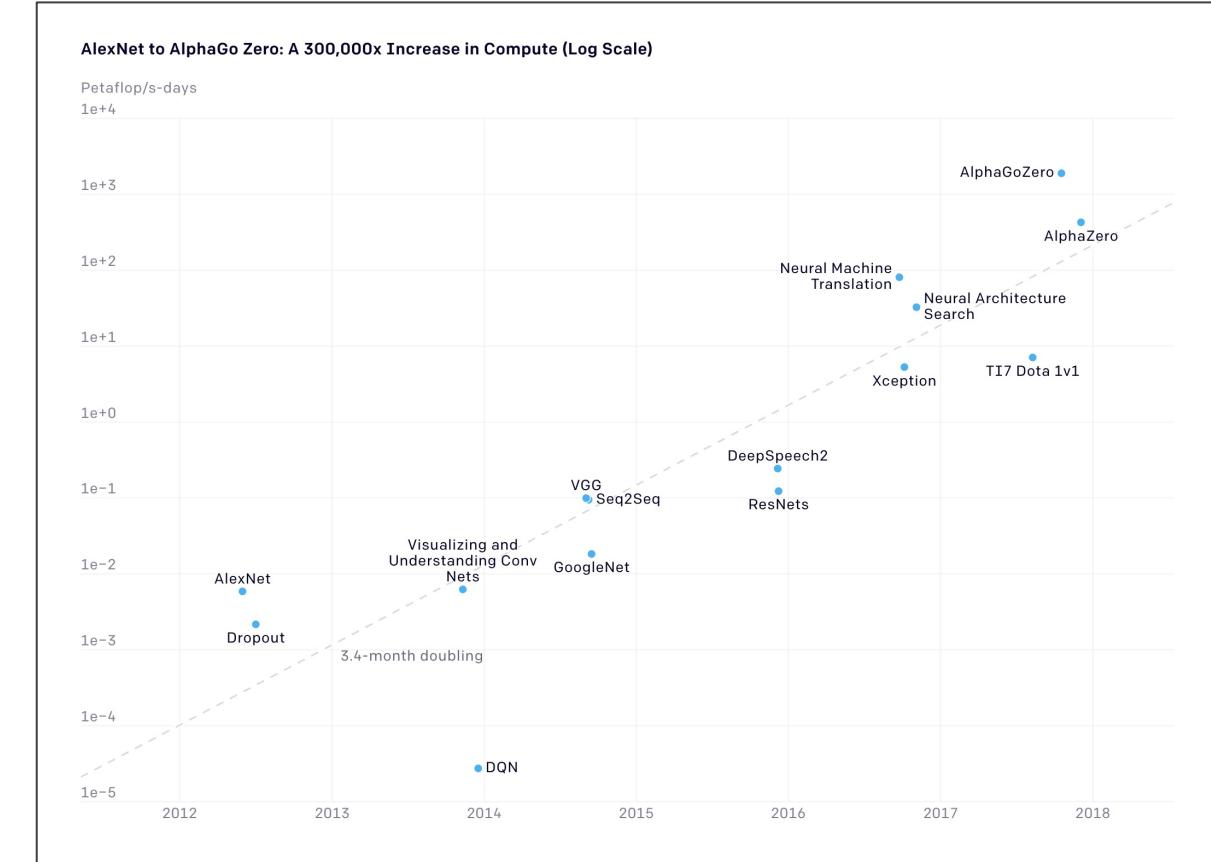
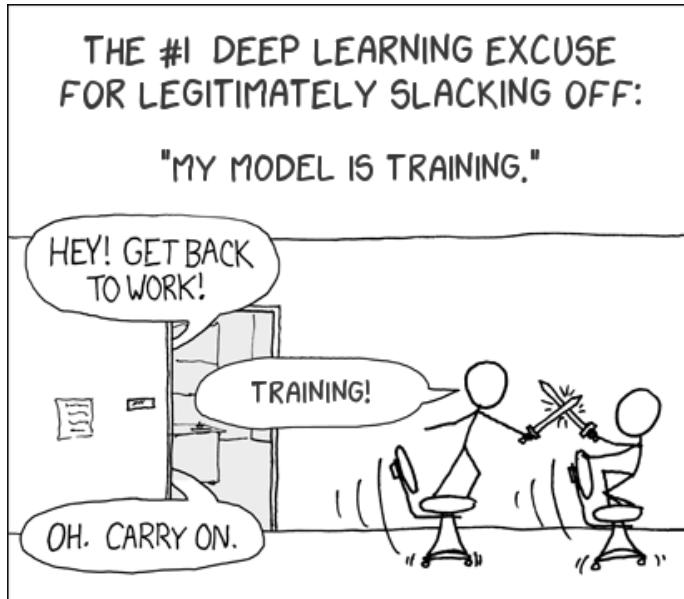
Source: A Survey on Distributed Machine Learning
<https://dl.acm.org/doi/abs/10.1145/3377454>

DL Training: The Phases

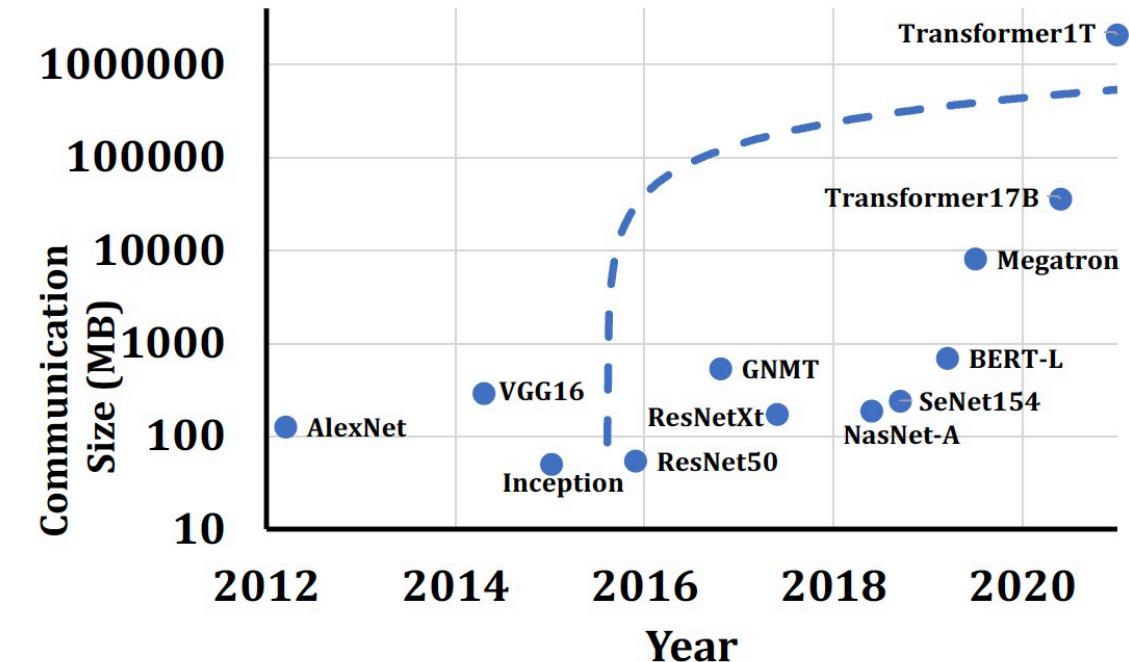
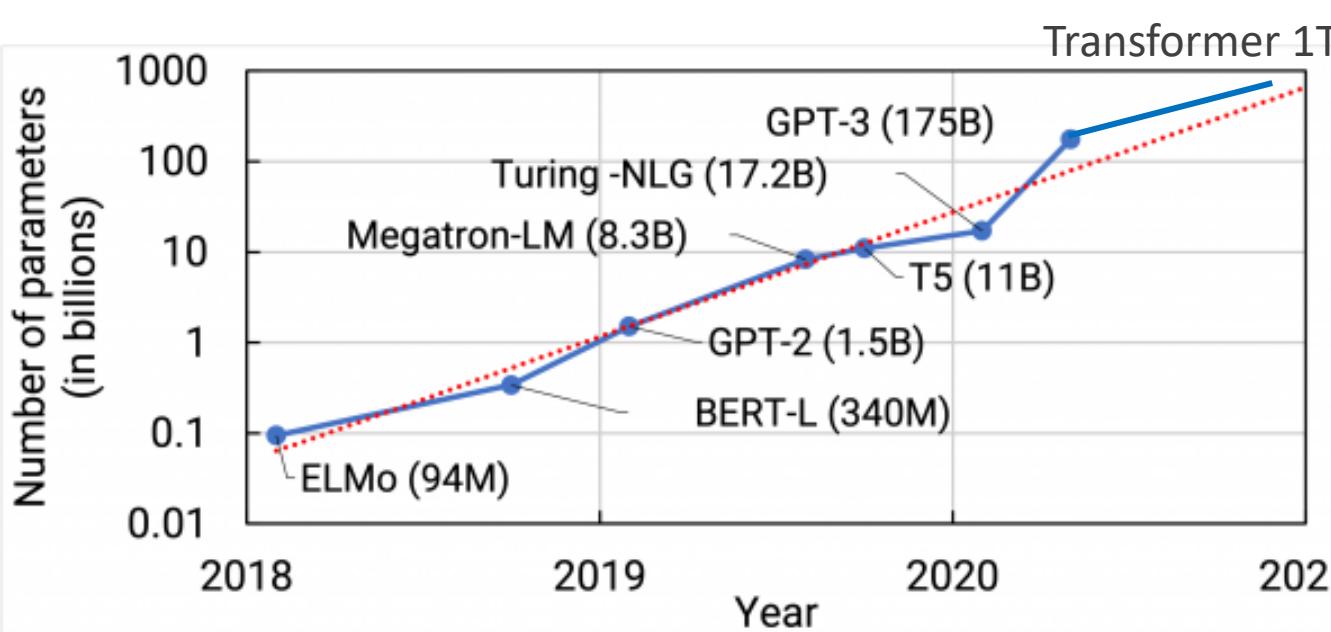
- Each training algorithm consists of 3 computation phases:
 - 1. Forward pass (inference):
 - The process of finding output activations using inputs and weights.
 - 2. Weight gradient computation:
 - The process of finding the gradient of weights (with respect to the loss function) using output gradients and inputs.
 - 3. Input gradient computation:
 - The process of finding the gradient of inputs (with respect to the loss function) using output gradients and weights.
- Operations 2 & 3 together are called backpropagation.
- The **training loop** dictates the order in which we issue the basic operations and (possibly) their related communication tasks.

Deep Learning Training Challenge

- **Training time is increasing**
 - DNNs are becoming larger
 - Turing NLG: 17.2 B Parameters
 - Megatron LM: 8.3B Parameters
 - Training samples are becoming larger
 - Moore's Law has ended



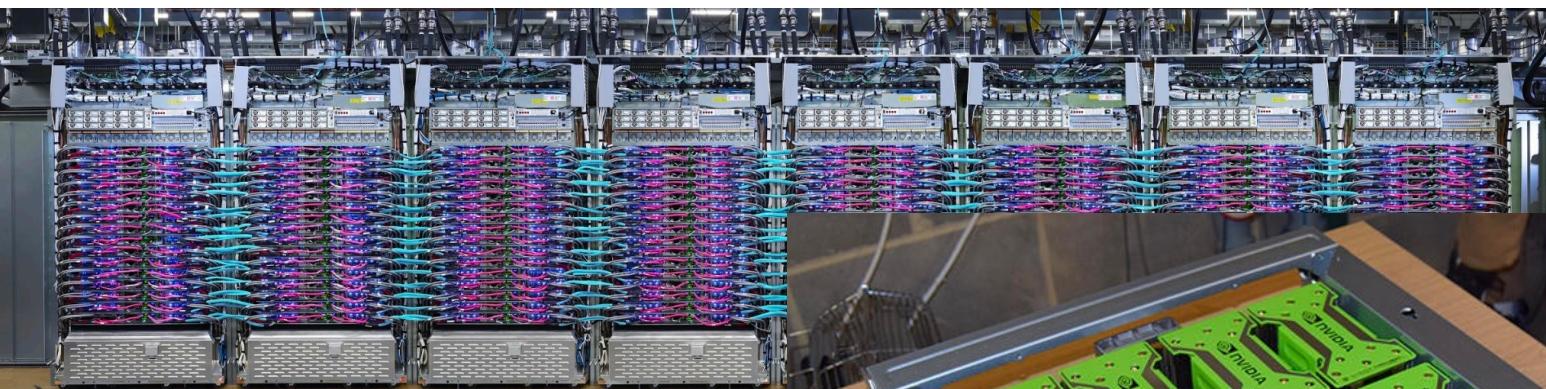
Key Challenge: Large Models → Large Comms



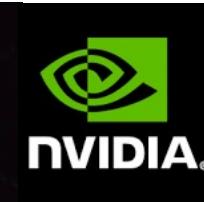
Challenges:

- Multiple NPUs are required to fit large-scale models
- e.g., 16 NPUs for GPT-3 (175B params)
128 NPUs for Transformer-1T (1T params) (using ZeRO stage 2)

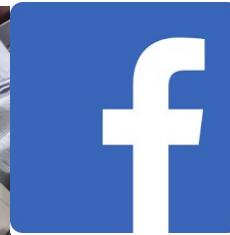
Enter: DL Training Platforms



Google TPU v3



DGX 2



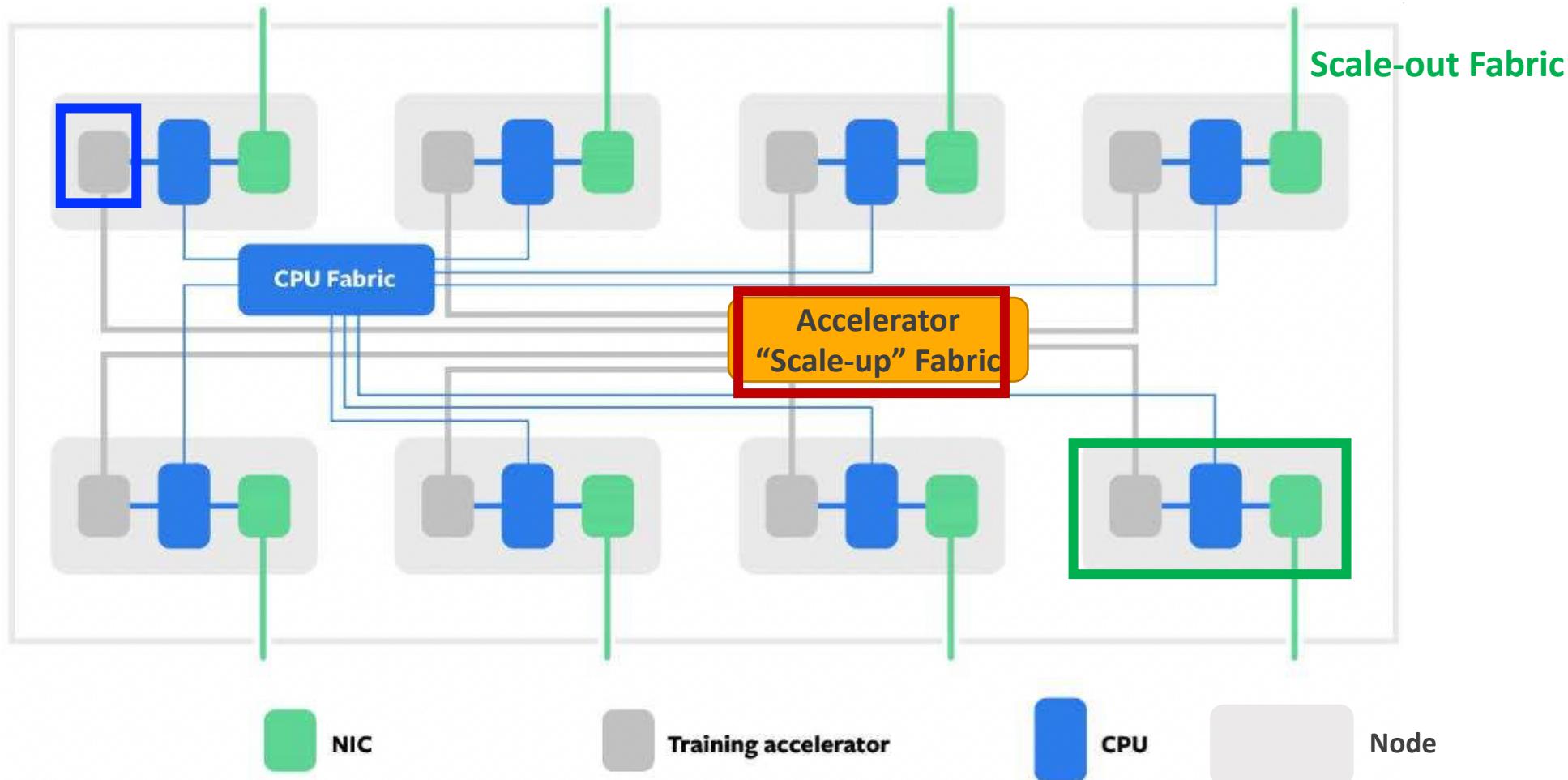
Zion

- ✓ Build customized chips for training
- ✓ Scale the training across more compute nodes

And many more ...

- Cerebras CS2
- Tesla Dojo
- NVIDIA DGX + Mellanox SHARP switches
- Intel Habana
- IBM Blueconnect
- ...

Components of a DL Training Platform



Modified version of source figure from : "Zion: Facebook Next- Generation Large Memory Training Platform", Misha Smelyanskiy, Hot Chips 31"

Understanding DL Training design-space

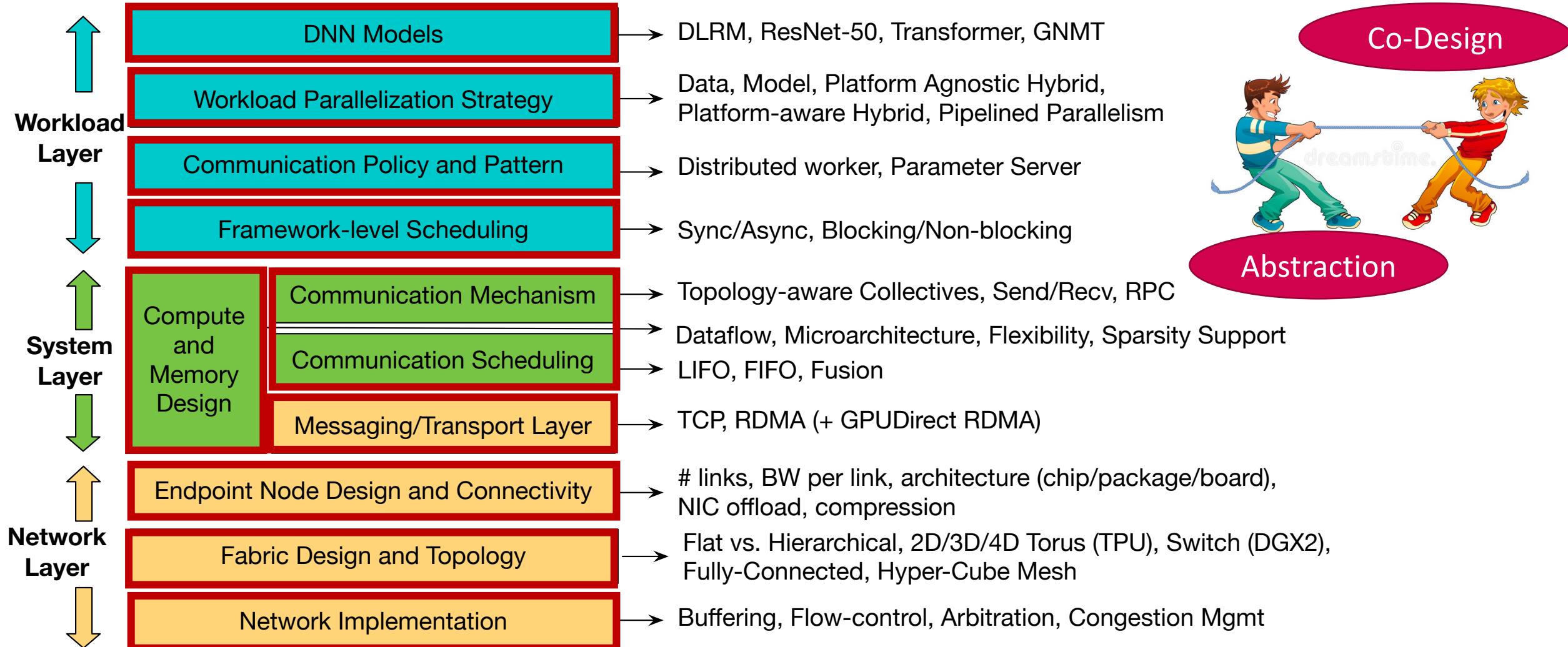


Figure Courtesy: Srinivas Sridharan (Facebook)

Distributed Training Stack

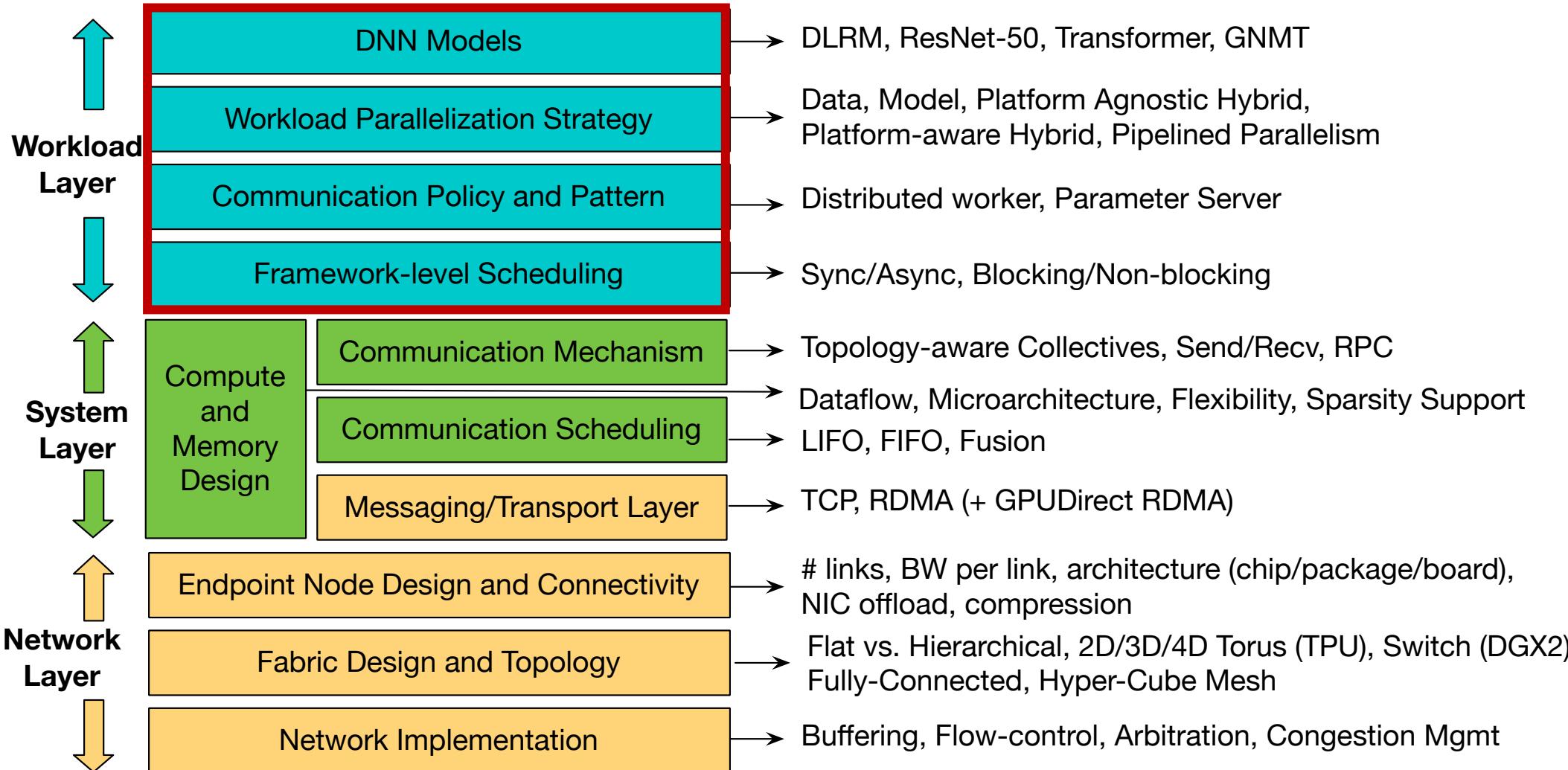
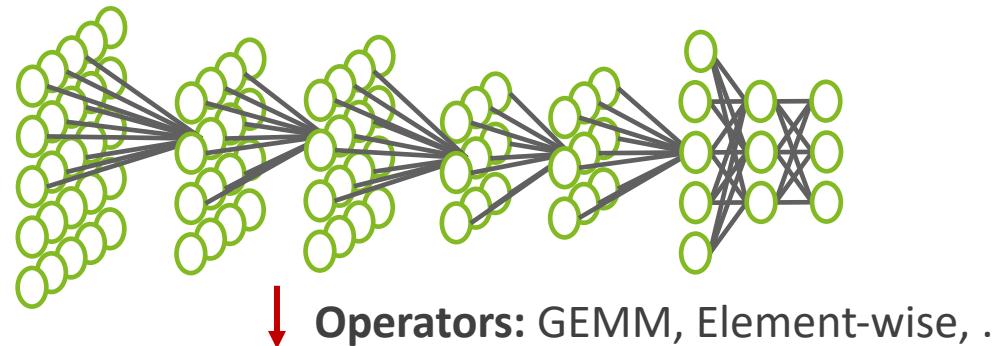
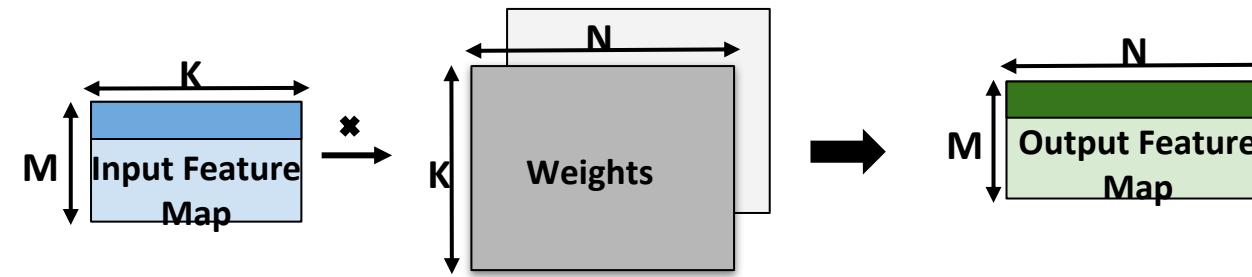


Figure Courtesy: Srinivas Sridharan (Facebook)

DNN Model



Forward Pass (Inference and Training)



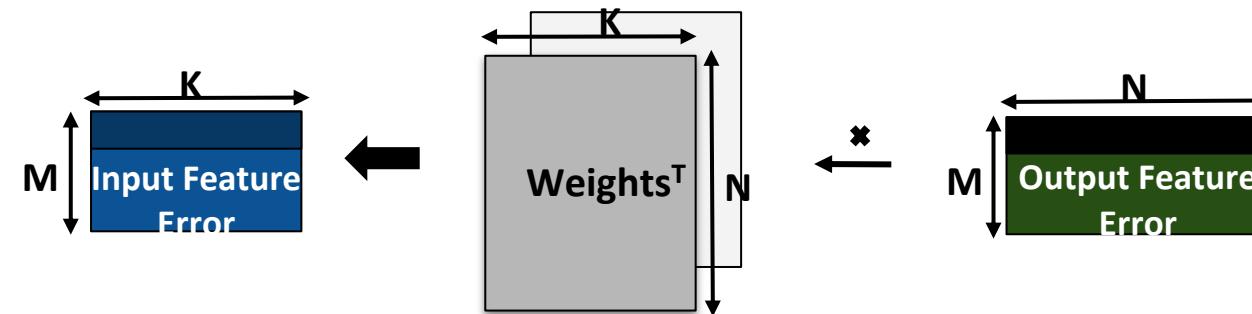
GEMM MNK
Dimension Representation

M dim: batch size

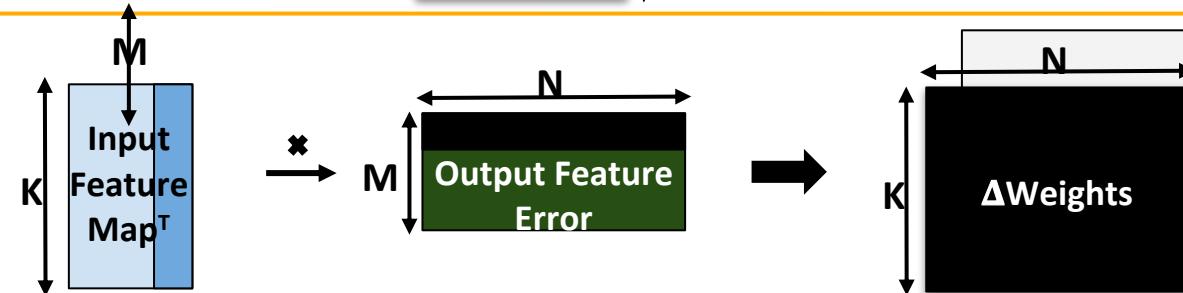
N dim: number of channels in the next layer

K dim: $[H * W * C]$

Backward Pass (Training)



Gradient Computation (Training)

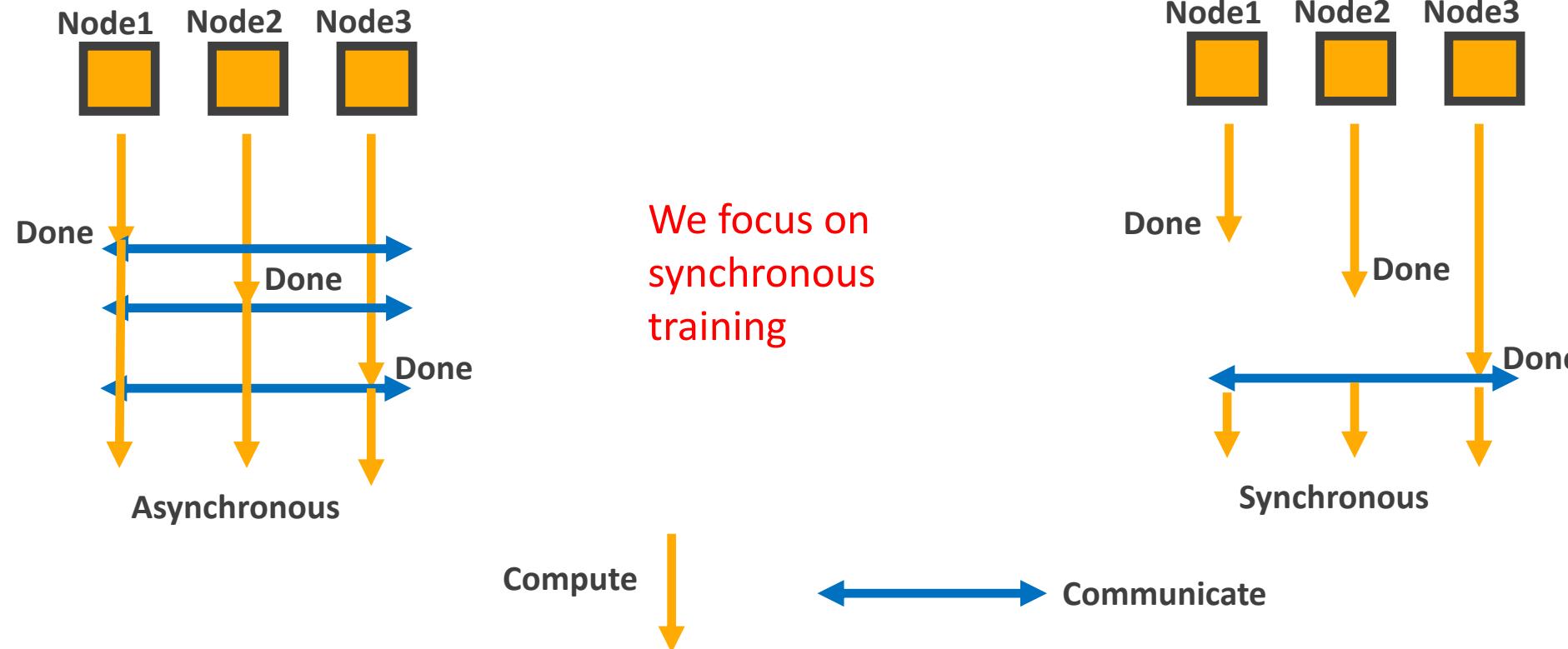


Model Parameter Update Mechanisms

		Synchronization	
		Asynchronous	Synchronous
Communication Handling	Parameter-server	Centralized or Distributed	Centralized or Decentralized
	Collective-based	N/A	Distributed

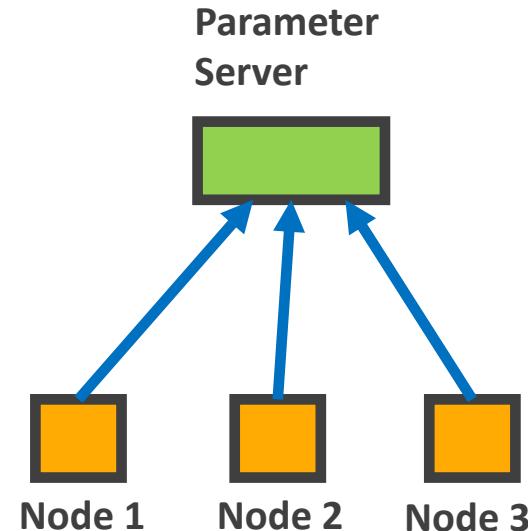
Synchronization: Sync. vs. Async. Training

- Defines when nodes should exchange data
 - Affects convergence time

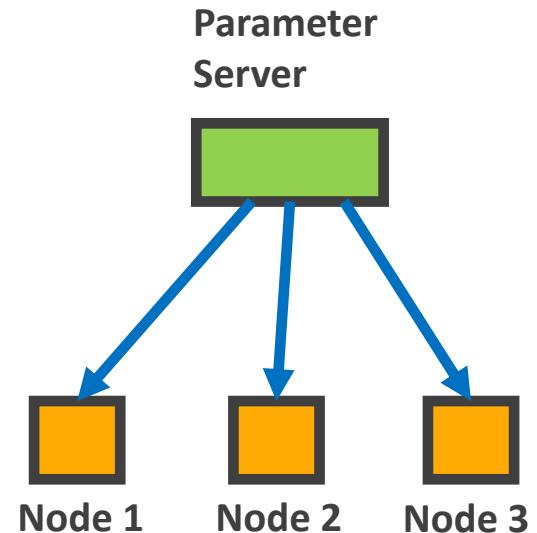


Communication Handling

- Parameter Server



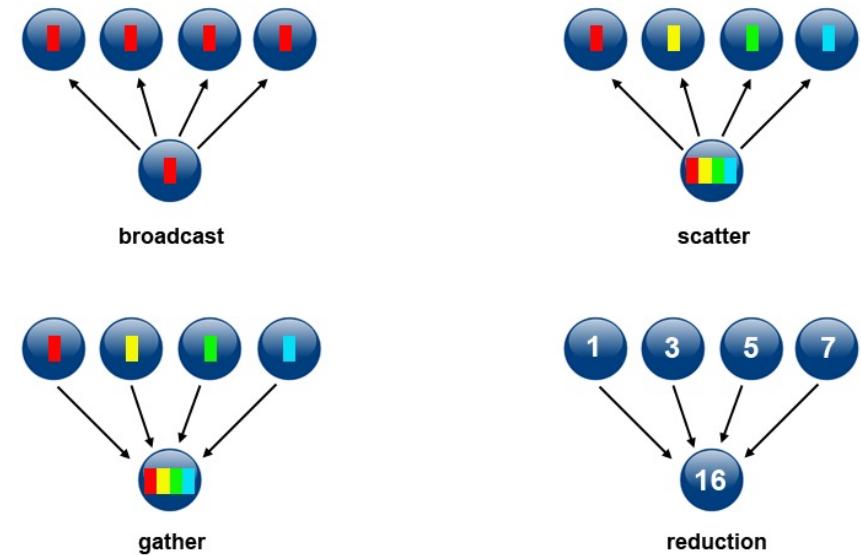
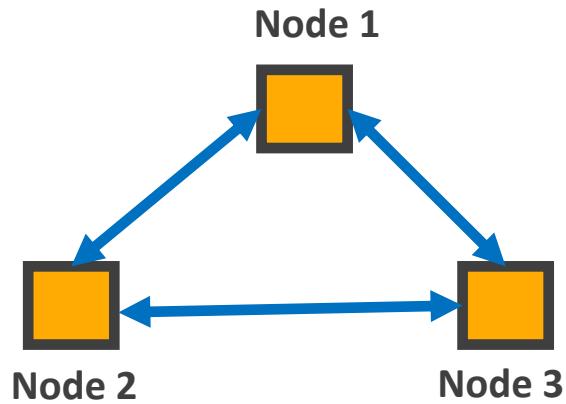
Step 1: Each node sends its model gradients to the parameter server to be reduced with other gradients and update the model



Step 2: The parameter server sends the updated model to the compute nodes to begin the new iteration.

Communication Handling

- **Collective-based:** Compute Nodes directly talk to each other to globally reduce their gradients and update the model through *All-Reduce* communication pattern.



“Collective Communication”
(from MPI)

More details later

Exchanging Output Activations or Input Gradients:

- It may be required depending on the **parallelization strategy** (discussed next)
- Handled either via **collective based patterns** or direct **Node-to-Node sends/recvs** (no parameter server is used).

Parallelization Strategies

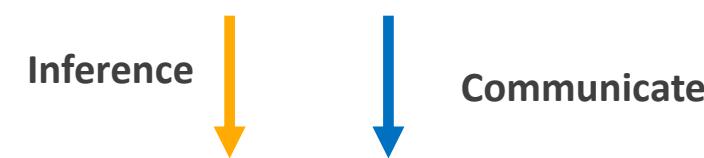
- The way compute tasks are distributed across different compute nodes. Multiple ways to split the tasks:
 - Split the minibatch (**Data-Parallel**)
 - Split the model (**Model-Parallel**)
 - Split the DNN layers: (**Pipeline-Parallel**)
 -
- This also defines the communication pattern across different nodes.

Parallelism: Data-Parallel Training

- Distribute Data across multiple nodes and replicate model (network) along all nodes.
- **No communication during the forward pass.**

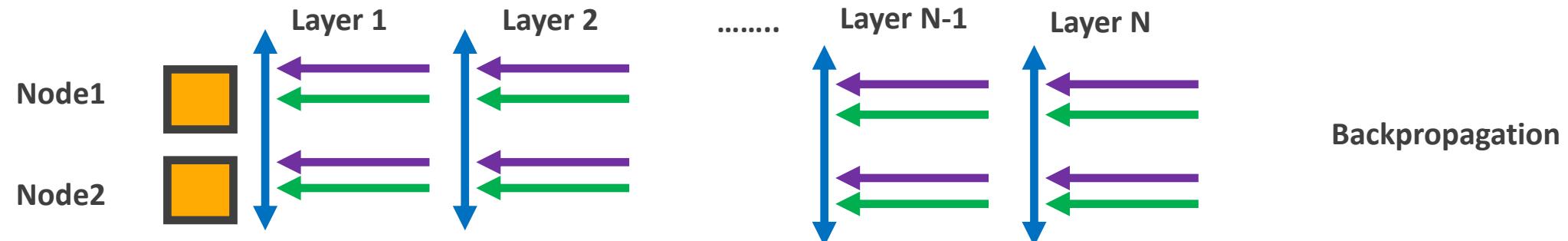


Flow-per-layer: 1. Compute output -> 2. go to the next layer

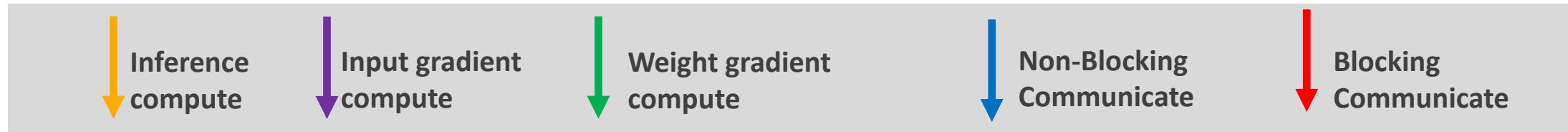


Parallelism: Data-Parallel Training

- Distribute Data across multiple nodes and replicate model (network) along all nodes.
- **Communicate weight gradients** during the backpropagation pass.
 - Blocking wait during forward pass for collective of previous backpropagation for that layer.

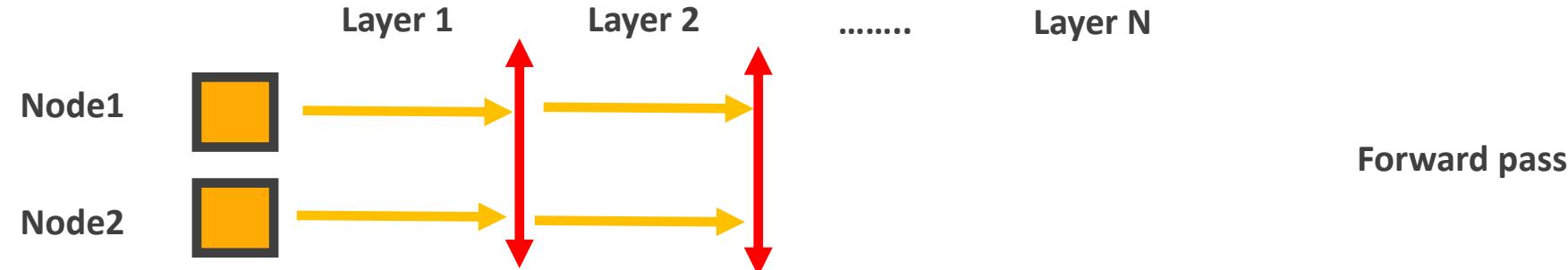


Flow-per-layer: 1. Compute weight gradient-> 2.issue weight gradient comm -> 3.compute input gradient -> 4. go to previous layer

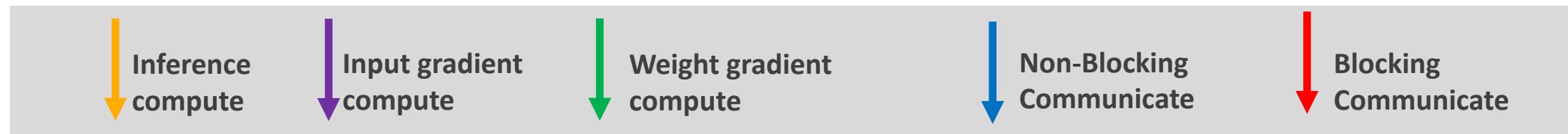


Parallelism: Model-Parallel Training

- Distribute Model across all nodes and replicate data along all nodes.
- **Communicate outputs** during the forward pass.

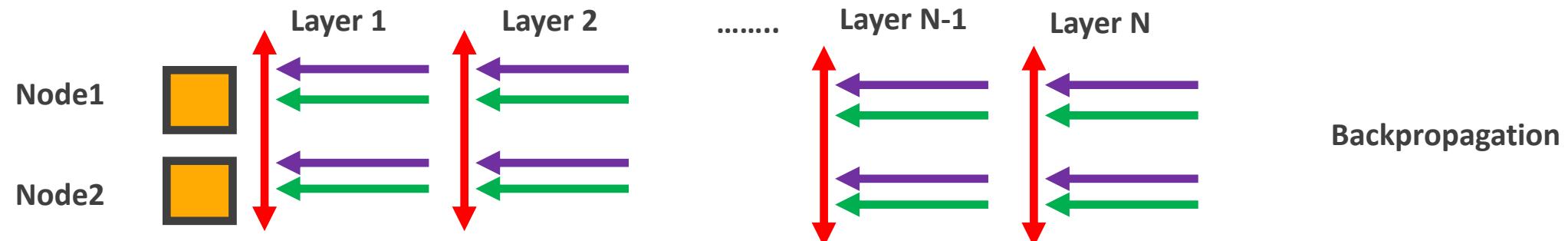


Flow-per-layer: 1. Compute output -> 2. issue output gradient comm -> 3. wait for gradient to be finished -> 4. go to the next layer

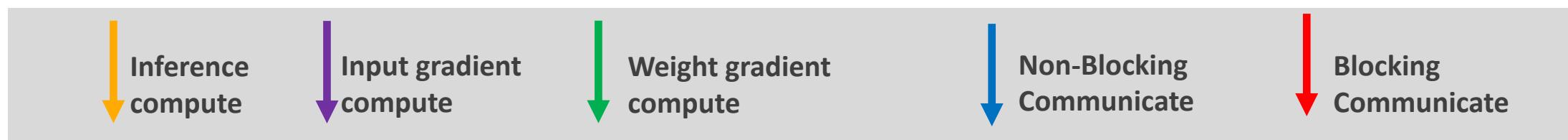


Parallelism: Model-Parallel Training

- Distribute Model across all nodes and replicate data along all nodes
- **Communicate input gradients** during the backpropagation pass.

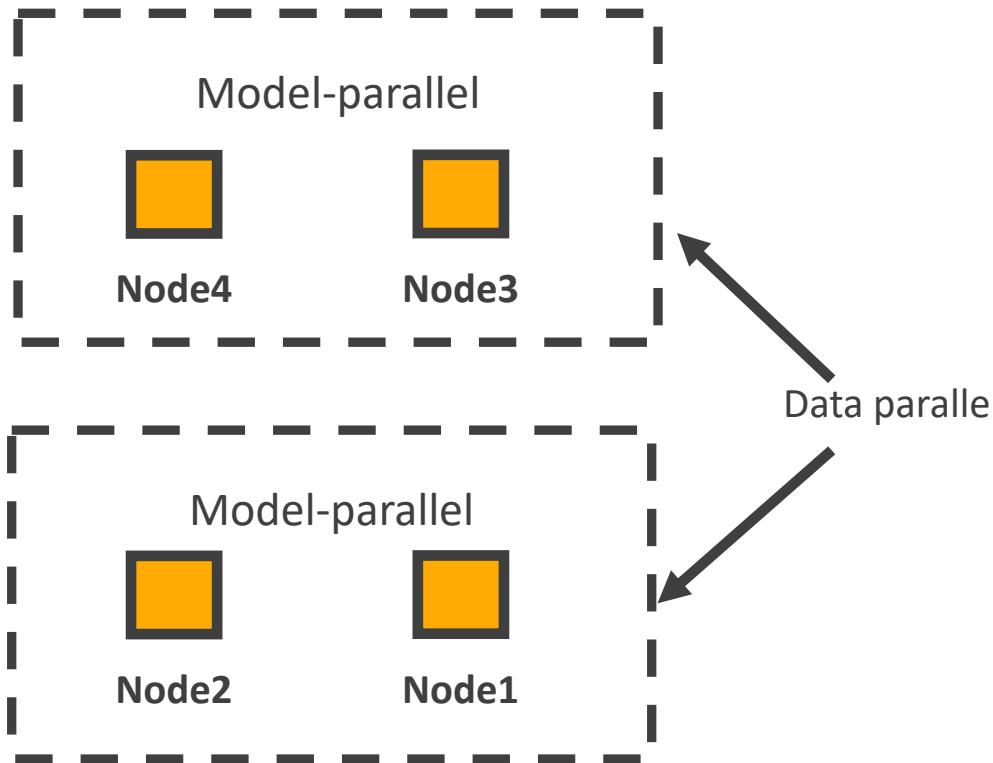


Flow-per-layer: 1. Compute input gradient-> 2.issue input gradient comm -> 3.compute weight gradient -> 4. wait for input gradient -> 5. go to previous layer



Parallelism: Hybrid Parallel

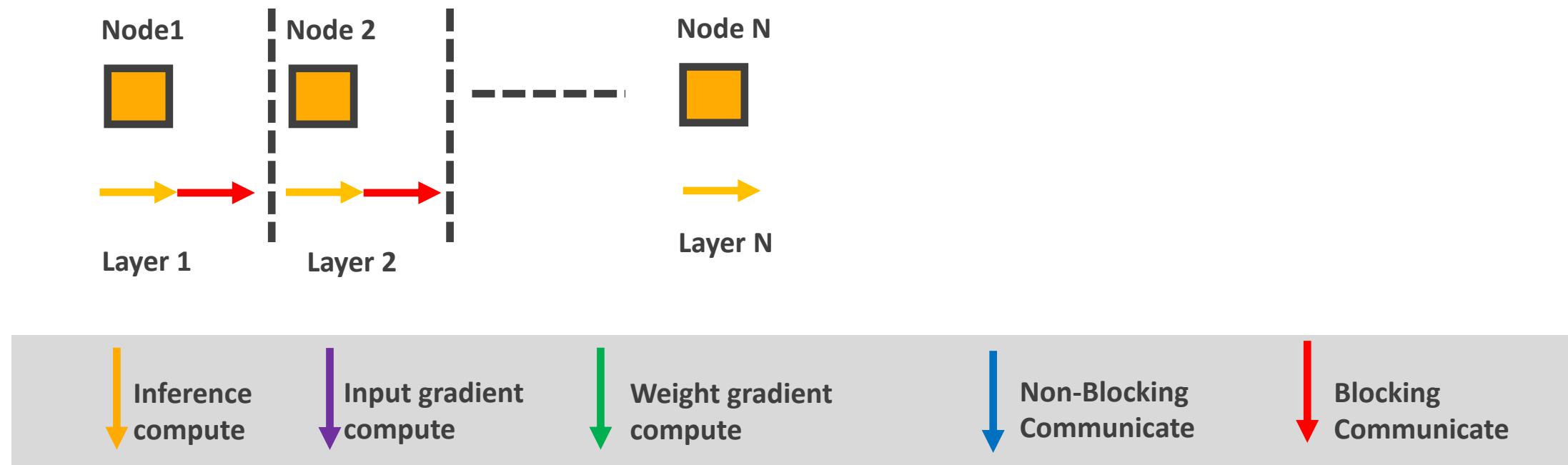
- Partition nodes into groups. Parallelism within a group is model-parallel, across the groups is data-parallel, or vice versa.



Parallelism	Activations during the forward pass	Weight gradients	Input gradients
Data		✓	
Model	✓		✓
Hybrid	partially	partially	partially

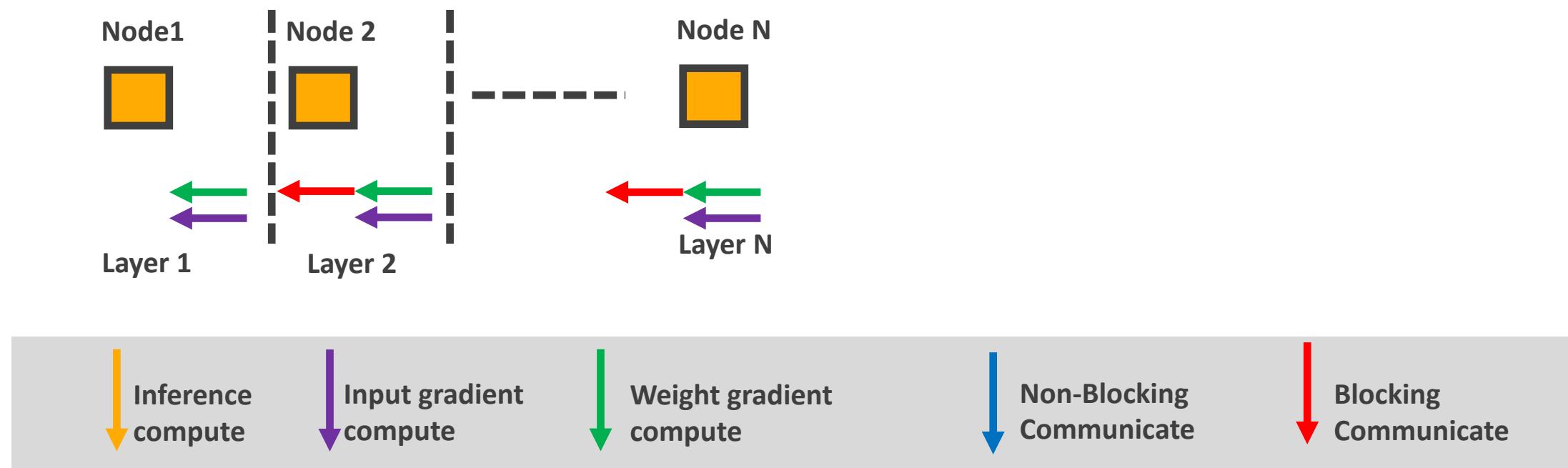
Parallelism: Pipelined Parallel

- Distribute DNN layers across all nodes.
- Decompose minibatch into microbatches and propagate them to the pipeline in-order.
- **Communicate outputs** during the forward pass.



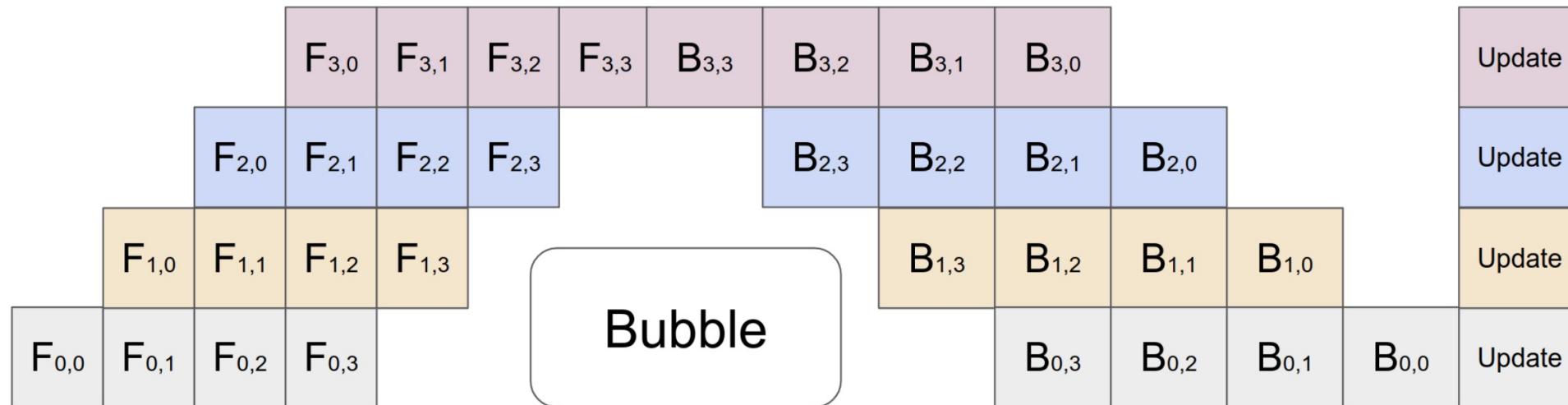
Parallelism: Pipelined Parallel

- Distribute DNN layers across all nodes.
- Decompose minibatch into microbatches and propagate them to the pipeline in-order.
- **Communicate input gradients** during the backpropagation.



Parallelism: Pipelined Parallel

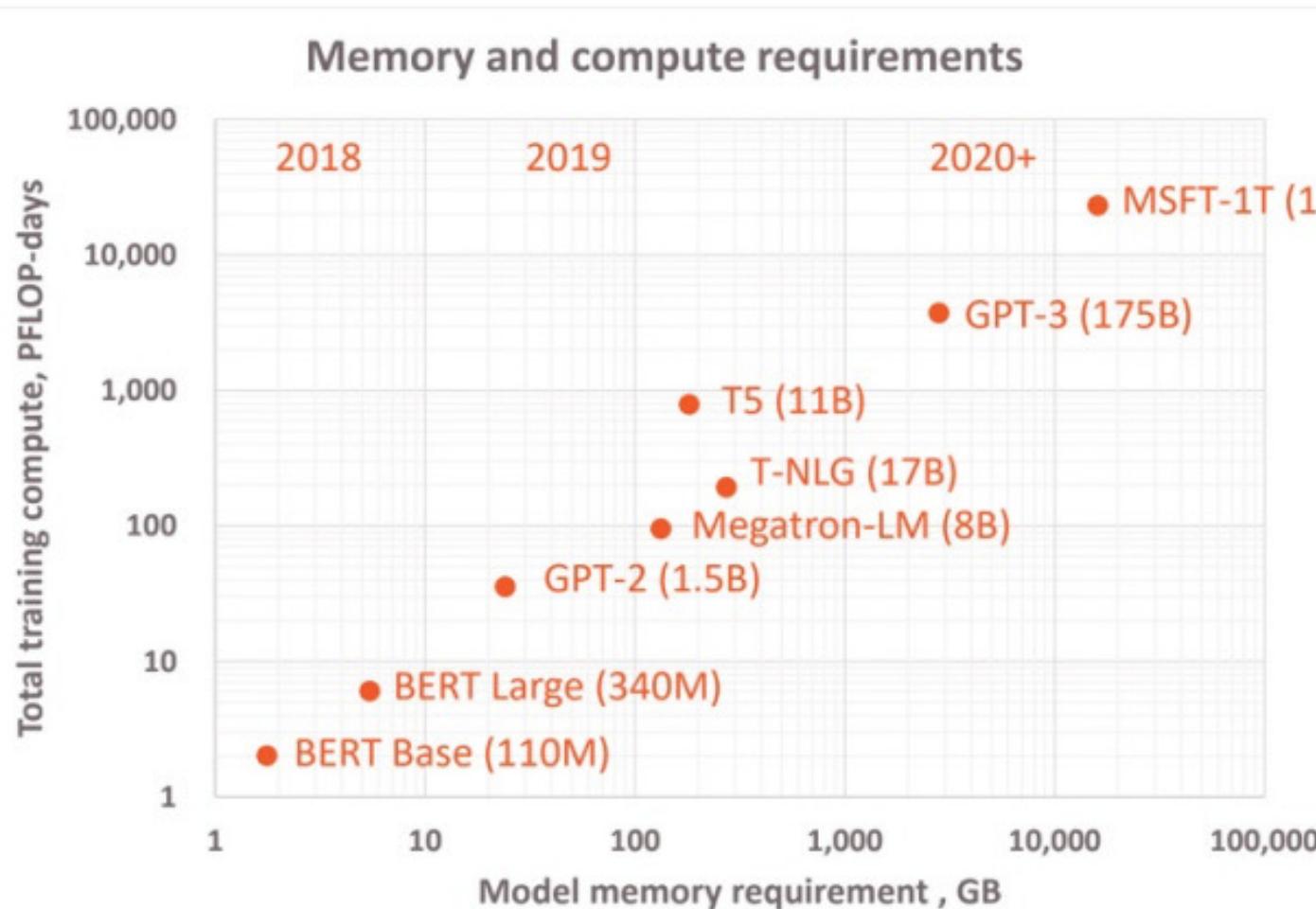
- How a minibatch is broken into micro-batches and pipeline is filled.



$F_{m,n}$: forward-pass corresponding to micro-batch #n at device #m.

$B_{m,n}$: back-propagation corresponding to micro-batch #n at device #m.

Need for more sophisticated schemes ...



1000x **larger models**
1000x **more compute**
In just **2 years**

Today, GPT-3 with 175 billion params trained on 1024 GPUs for 4 months.

Tomorrow, **multi-Trillion** parameter models and beyond.

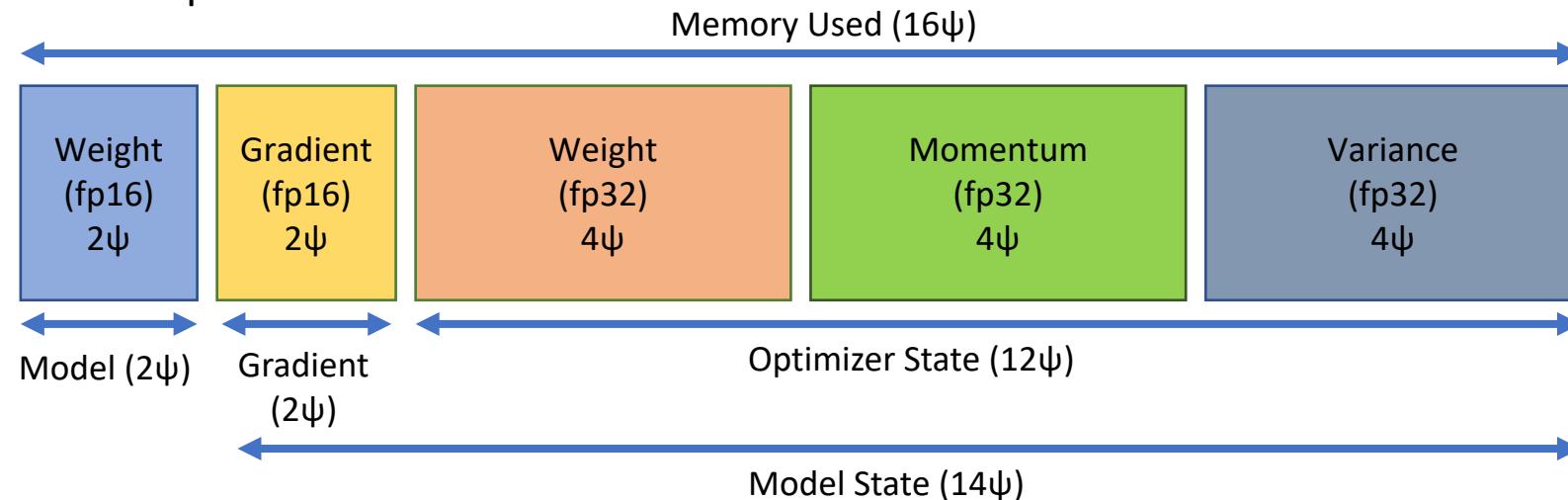
Source: Cerebras (Hot Chips 2021)

Example 1: Microsoft ZeRO

- Motivation

- Data Parallelism (DP): Cannot fit large models
- Model Parallelism (MP): Computations too fine-grained, Large communication overhead, Layer-dependent design
- Large Memory Overhead for Model + Optimizer state
 - **8x overhead over model state!**

#Parameters: ψ



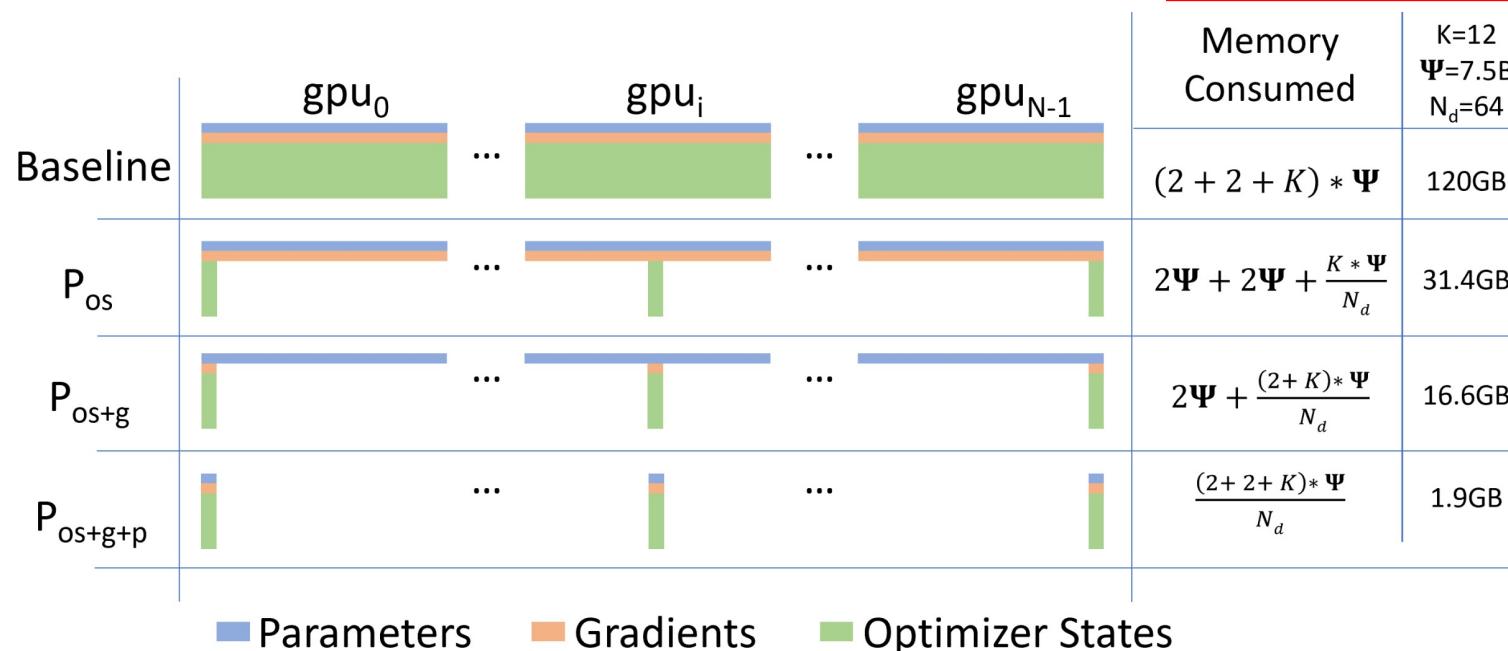
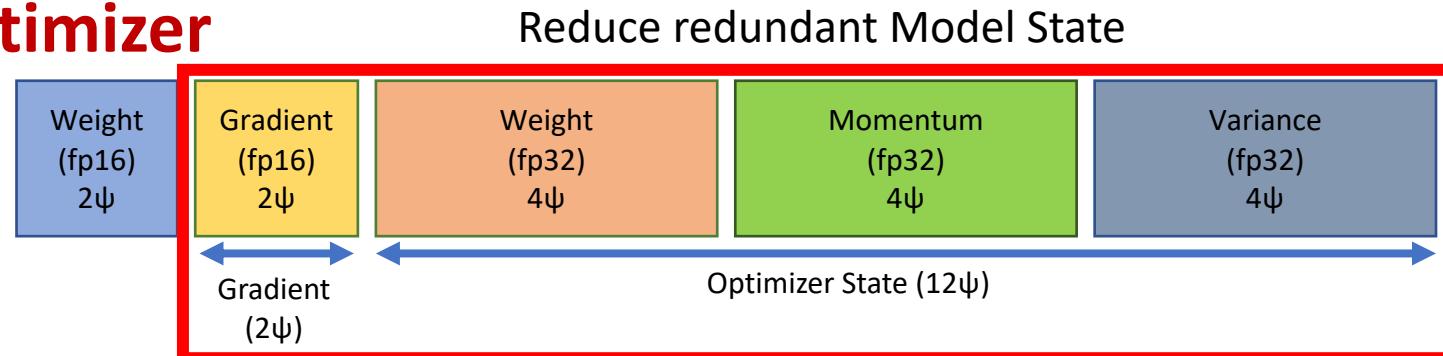
<https://www.microsoft.com/en-us/research/blog/zero-deepspeed-new-system-optimizations-enable-training-models-with-over-100-billion-parameters/>

Example 1: Microsoft ZeRO

- **ZeRO: Zero Redundancy Optimizer**

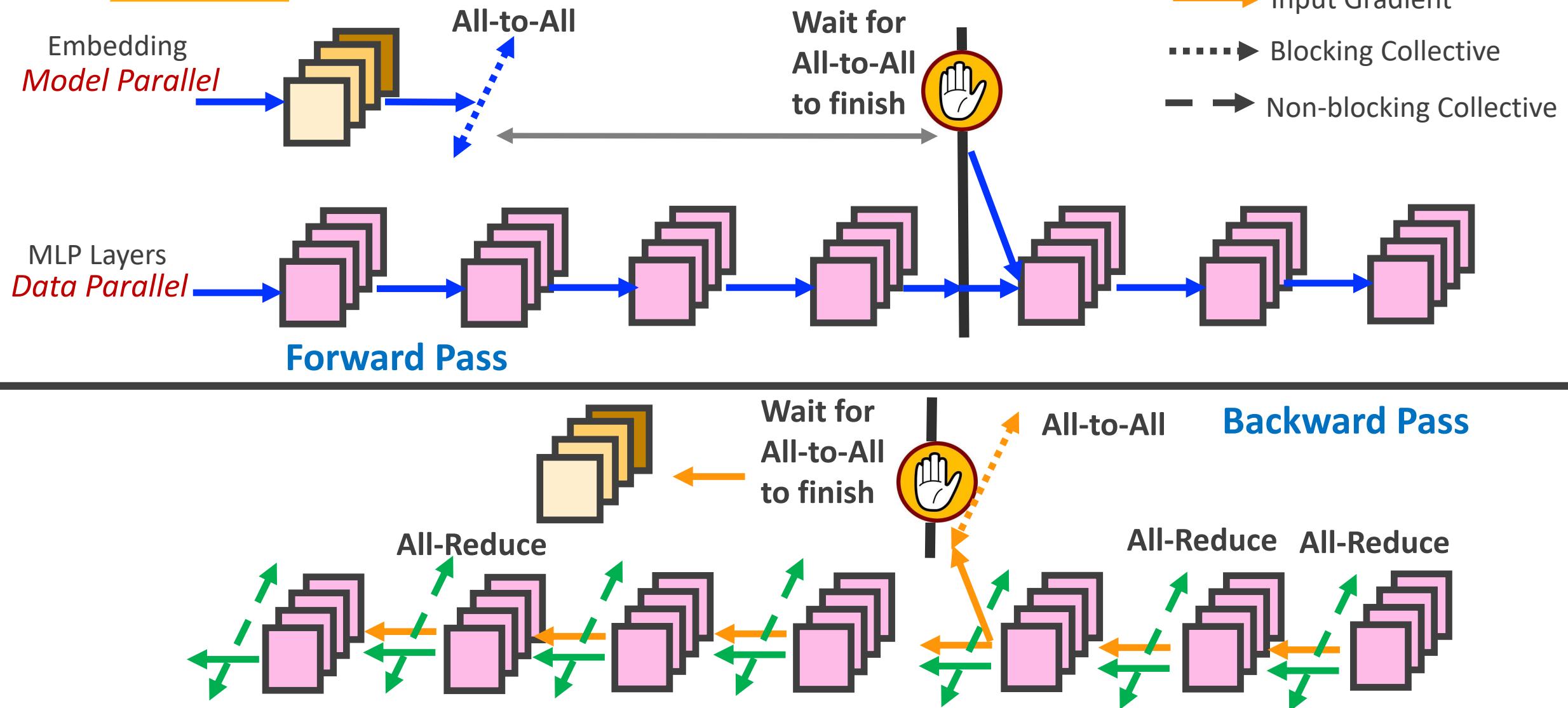
- Partition Optimizer state
- Partition Gradient state

- Memory vs Communication

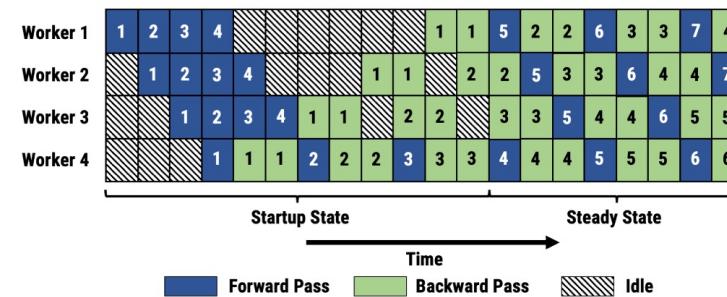
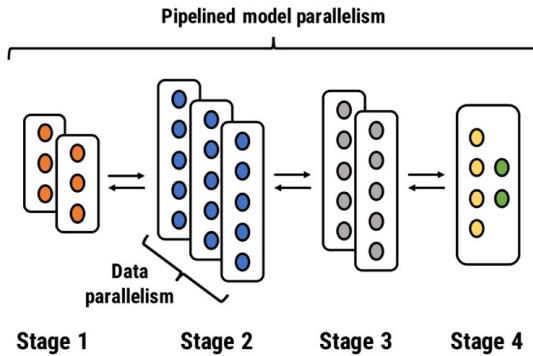


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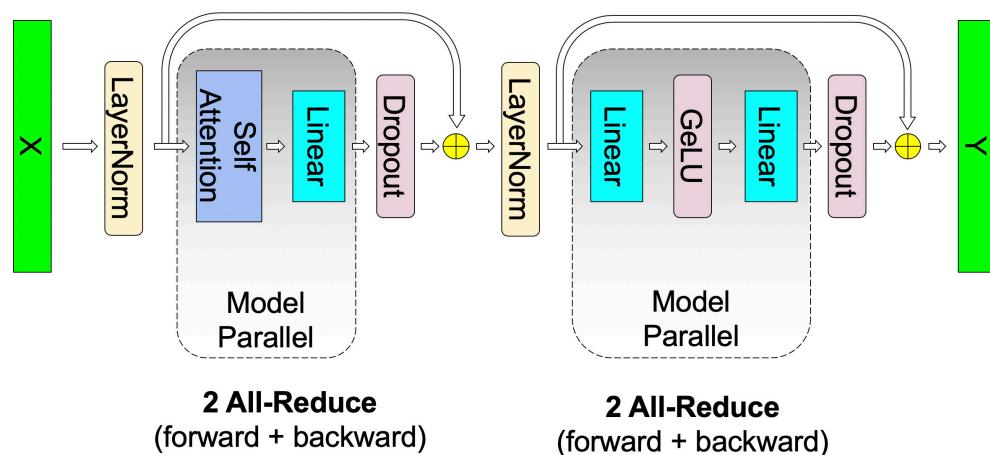
Example 2: Facebook DLRM



More recent examples



PipeDream (Microsoft)



MegatronLM (NVIDIA)

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 Brilliant Minds. Breakthrough Discoveries. GTC | November 8 - 11, 2022

DEVELOPER BLOG

Oct 11, 2021 English ▾

Using DeepSpeed and Megatron to Train Megatron-Turing NLG 530B, the World's Largest and Most Powerful Generative Language Model

By Paresh Kharya and Ali Alvi

Discuss (0) Share 0 Like

Tags: Conversational AI / NLP, DGX SuperPOD, HPC / Supercomputing, Megatron, Technical Walkthrough

A log-log plot showing the exponential growth of model size over time. The Y-axis represents Model Size (in billions of parameters) on a logarithmic scale from 0.01 to 1000. The X-axis represents the year from 2018 to 2022. Data points are connected by a dashed line, showing the progression from ELMo (94M) in 2018 to Megatron-Turing NLG (530B) in 2022.

Model	Year	Size (billions of parameters)
ELMo	2018	~0.1
BERT-Large	2019	~0.3
GPT-2	2019	~1.5
T5	2020	~11
GPT-3 (175B)	2020	~175
Megatron-LM (8.3B)	2020	~8.3
Megatron-Turing NLG (530B)	2021	~530
Turing-NLG (17.2B)	2021	~17.2

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Tushar Krishna | Georgia Institute of Technology

February 28, 2022

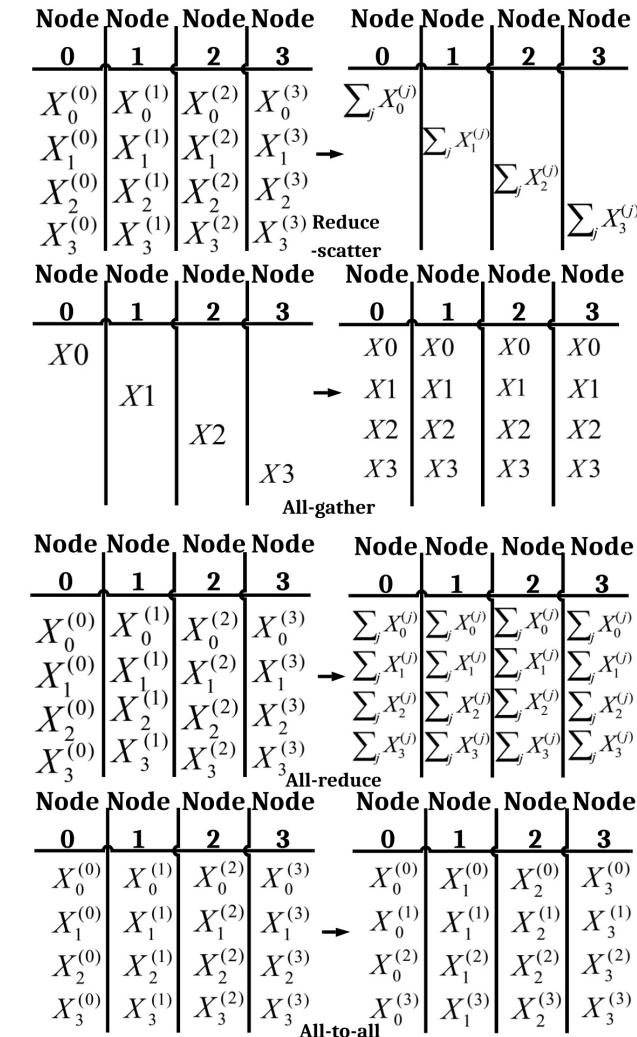
When are collectives needed?

	Model Updates	Input Gradient Exchange	Output Activation Exchange
Param-server	N	Data-parallel: N Model-parallel: Usually* Pipeline-Parallel: N	Data-parallel: N Model-parallel: Usually* Pipeline-Parallel: N
Collective-based	Y (All-Reduce)	Data-parallel: N Model-parallel: Usually* Pipeline-Parallel: N	Data-parallel: N Model-parallel: Usually* Pipeline-Parallel: N

* All-reduce, All-gather, Reduce-scatter, All-to-All

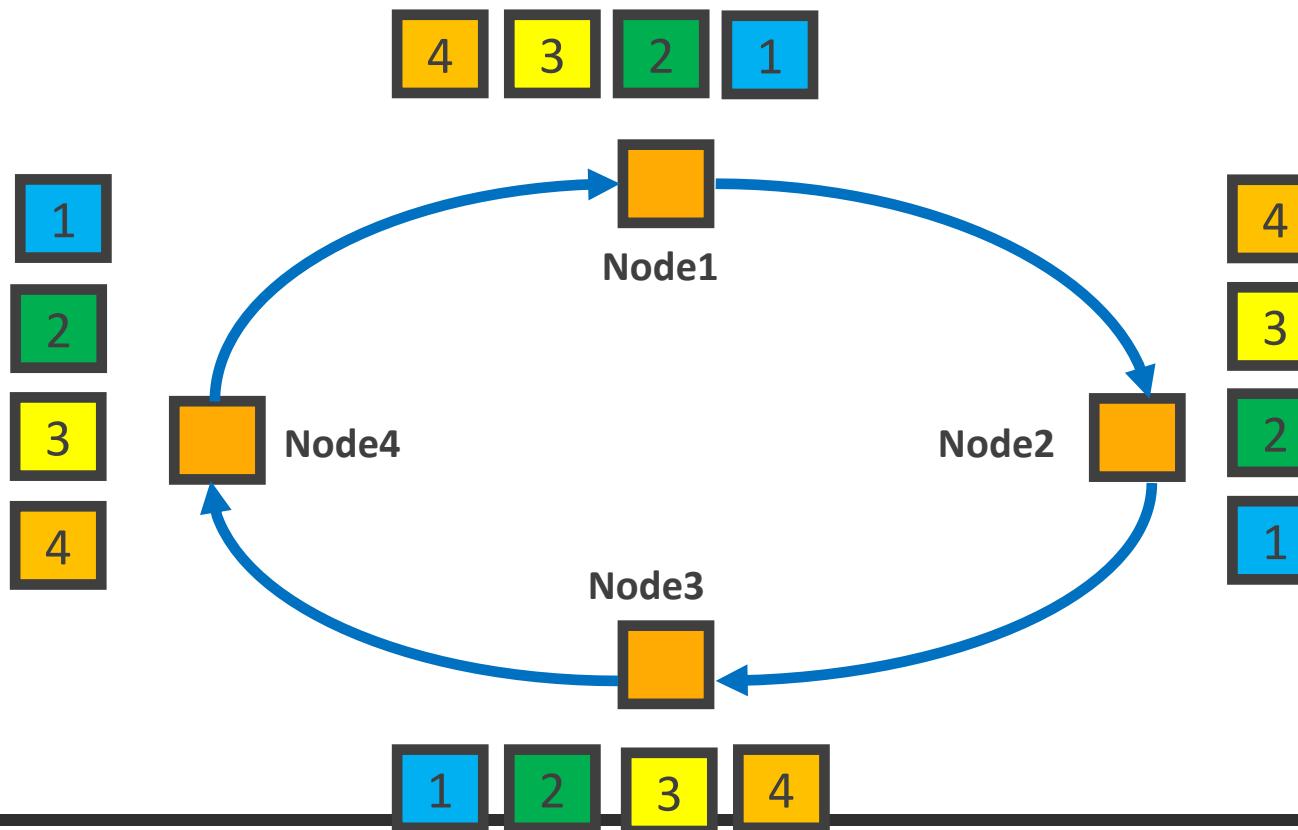
Different Kinds of Collective Algorithms

- Reduce-Scatter:
 - Used during input-output exchange due to model-parallelism
 - Implementation Algorithms: **Ring-Based, Direct-based, etc.**
- All-Gather:
 - Used during input-output exchange due to model-parallelism
 - Implementation Algorithms: **Ring-Based, Direct-based, etc.**
- All-Reduce (Reduce-Scatter + All-Gather):
 - Used during input-output exchange due to model-parallelism, or during model-parameter update.
 - Implementation Algorithms: **Ring-Based, Direct-based, Tree-based, Halving-doubling, etc..**
- All-To-All:
 - Used during input-output exchange due to model-parallelism (e.g., distributed embedding layer on DLRM DNN.).
 - Implementation Algorithms: **Direct-based, Ring-Based, etc..**



Example: Ring Based All-Reduce

- A ring with N nodes partitions data to N messages
- Collective Communication Flow:



Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3
$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$	$\sum_j X_0^{(j)}$			
$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$		$\sum_j X_1^{(j)}$		
$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$			$\sum_j X_2^{(j)}$	
$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$				$\sum_j X_3^{(j)}$

Reduce-scatter

| Node |
|-------|-------|-------|-------|-------|-------|-------|-------|
| 0 | 1 | 2 | 3 | 0 | 1 | 2 | 3 |
| X_0 |
| X_1 |
| X_2 |
| X_3 |

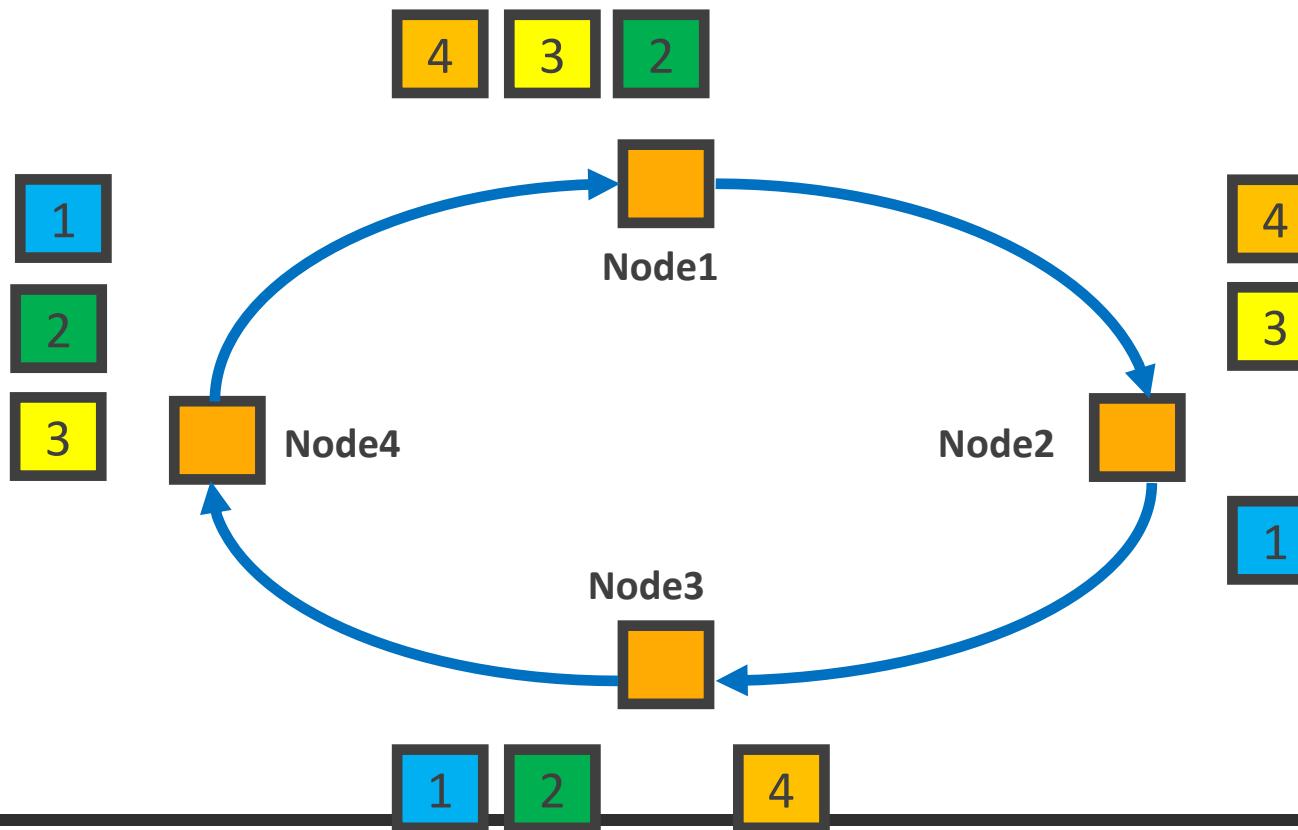
All-gather

Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3
$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$	$\sum_j X_0^{(j)}$	$\sum_j X_0^{(j)}$	$\sum_j X_0^{(j)}$	$\sum_j X_0^{(j)}$
$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$		$\sum_j X_1^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_1^{(j)}$
$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$			$\sum_j X_2^{(j)}$	$\sum_j X_2^{(j)}$
$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$				$\sum_j X_3^{(j)}$

All-reduce

Example: Ring Based All-Reduce

- A ring with N nodes partitions data to N messages
- Collective Communication Flow:



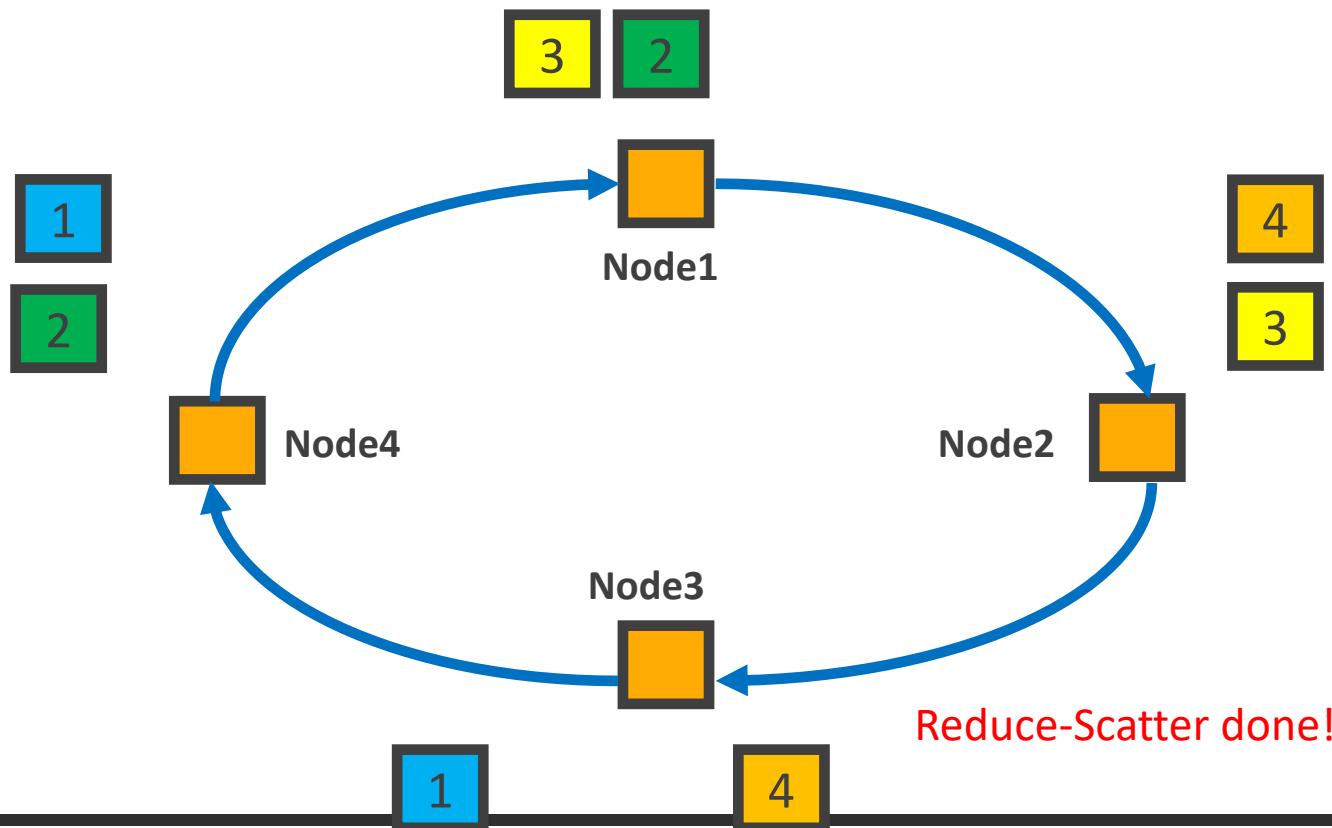
| Node |
|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $X_0^{(0)}$ | $X_0^{(1)}$ | $X_0^{(2)}$ | $X_0^{(3)}$ | $X_1^{(0)}$ | $X_1^{(1)}$ | $X_1^{(2)}$ | $X_1^{(3)}$ | $X_2^{(0)}$ | $X_2^{(1)}$ | $X_2^{(2)}$ | $X_2^{(3)}$ |
| $X_3^{(0)}$ | $X_3^{(1)}$ | $X_3^{(2)}$ | $X_3^{(3)}$ | X_0 | X_1 | X_2 | X_3 | X_0 | X_1 | X_2 | X_3 |
| X_0 | X_1 | X_2 | X_3 | X_0 | X_1 | X_2 | X_3 | X_0 | X_1 | X_2 | X_3 |
| X_1 | X_2 | X_3 | X_0 | X_1 | X_2 | X_3 | X_0 | X_1 | X_2 | X_3 | X_0 |
| X_2 | X_3 | X_0 | X_1 | X_2 | X_3 | X_0 | X_1 | X_2 | X_3 | X_0 | X_1 |
| X_3 | X_0 | X_1 | X_2 | X_3 | X_0 | X_1 | X_2 | X_3 | X_0 | X_1 | X_2 |

Annotations indicate the steps:

- Reduce-scatter:** The first row shows the initial data followed by the result of the reduce-scatter step.
- All-gather:** The second row shows the result of the all-gather step.
- All-reduce:** The third row shows the result of the all-reduce step.

Example: Ring Based All-Reduce

- A ring with N nodes partitions data to N messages
- Collective Communication Flow:



Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3	0	1	2	3
$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$	$\sum_j X_0^{(j)}$							
$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$		$\sum_j X_1^{(j)}$						
$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$			$\sum_j X_2^{(j)}$					
$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$				$\sum_j X_3^{(j)}$				

Reduce-scatter

| Node |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0 | 1 | 2 | 3 | 0 | 1 | 2 | 3 | 0 | 1 | 2 | 3 |
| X_0 | | | | X_0 |
| | X_1 | | | | X_1 |
| | | X_2 | | | | X_2 | X_2 | X_2 | X_2 | X_2 | X_2 |
| | | | X_3 | | | | X_3 | X_3 | X_3 | X_3 | X_3 |

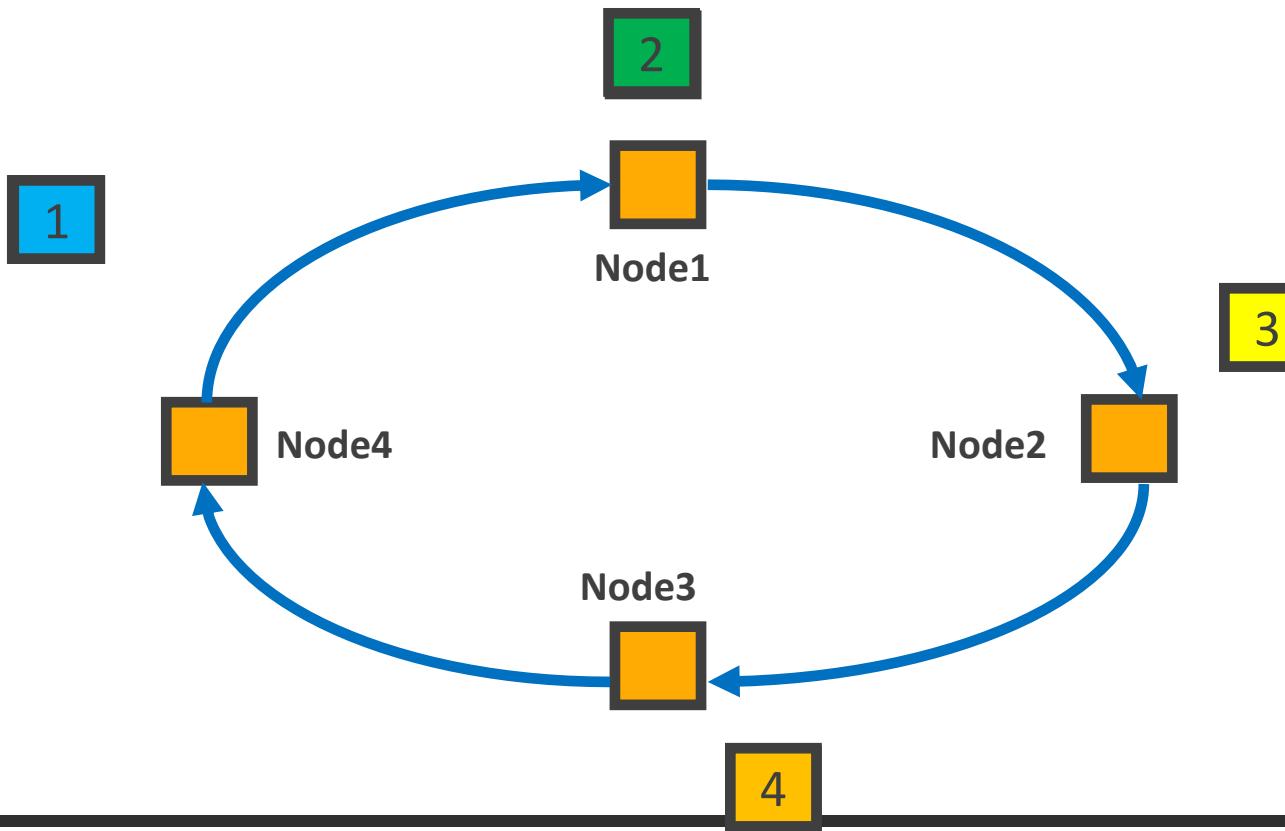
All-gather

Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3	0	1	2	3
$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$	$\sum_j X_0^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_3^{(j)}$	$\sum_j X_0^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_3^{(j)}$
$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$		$\sum_j X_1^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_3^{(j)}$	$\sum_j X_0^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_3^{(j)}$
$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$			$\sum_j X_2^{(j)}$	$\sum_j X_3^{(j)}$	$\sum_j X_0^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_3^{(j)}$
$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$				$\sum_j X_3^{(j)}$	$\sum_j X_0^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_3^{(j)}$

All-reduce

Example: Ring Based All-Reduce

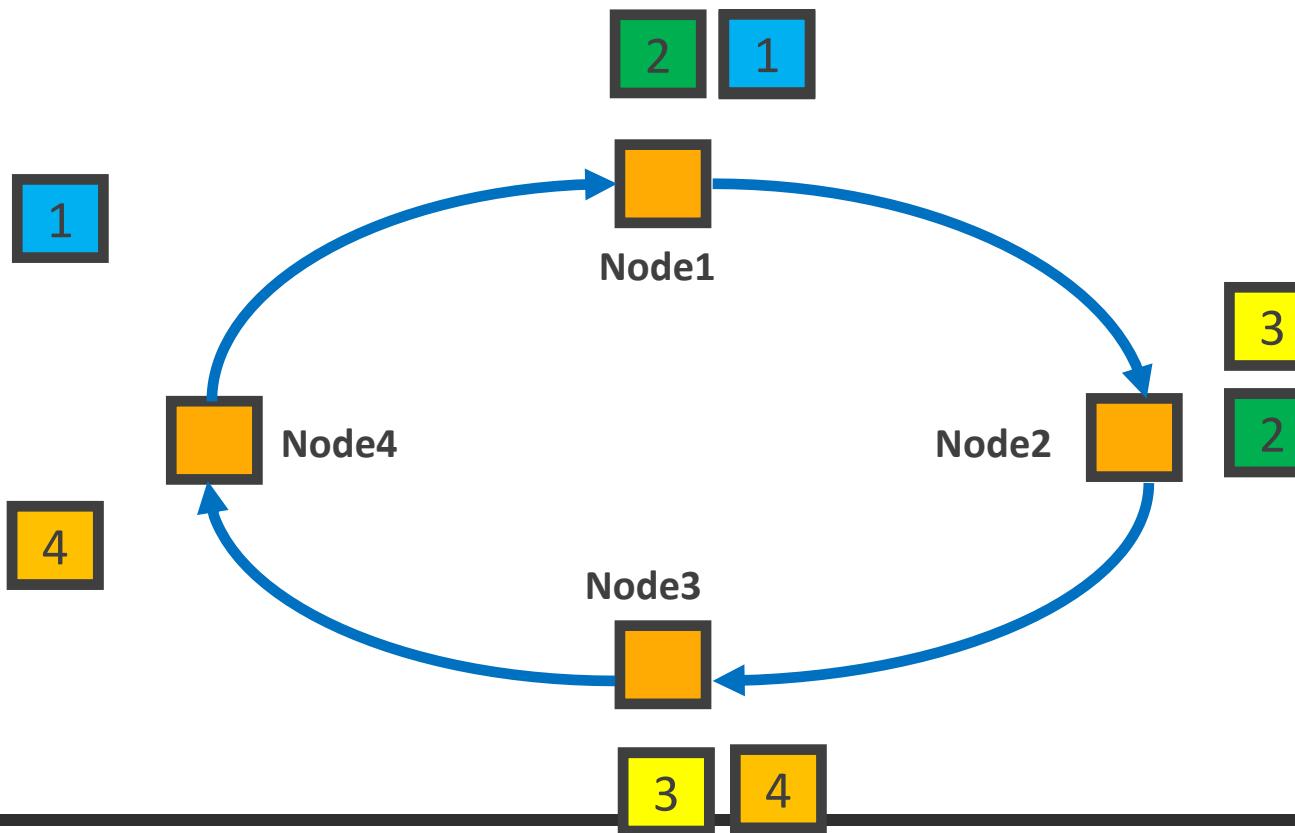
- A ring with N nodes partitions data to N messages
- Collective Communication Flow:



Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3	0	1
$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$	$\sum_j X_0^{(j)}$					
$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$		$\sum_j X_1^{(j)}$				
$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$			$\sum_j X_2^{(j)}$			
$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$				$\sum_j X_3^{(j)}$		
				Reduce	-scatter				
Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3	0	1
X_0				X_0	X_0	X_0	X_0		
	X_1				X_1	X_1	X_1		
		X_2				X_2	X_2	X_2	
			X_3				X_3	X_3	X_3
				All-gather					
Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3	0	1
$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$	$\sum_j X_0^{(j)}$	$\sum_j X_0^{(j)}$	$\sum_j X_0^{(j)}$	$\sum_j X_0^{(j)}$		
$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$		$\sum_j X_1^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_1^{(j)}$	
$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$			$\sum_j X_2^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_2^{(j)}$	
$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$				$\sum_j X_3^{(j)}$	$\sum_j X_3^{(j)}$	
				All-reduce					

Example: Ring Based All-Reduce

- A ring with N nodes partitions data to N messages
- Collective Communication Flow:



Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$	$\sum_j X_0^{(j)}$	$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$	$\sum_j X_1^{(j)}$	$X_2^{(0)}$	$X_2^{(1)}$
$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$	$\sum_j X_1^{(j)}$	$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$	$\sum_j X_2^{(j)}$	$X_3^{(0)}$	$X_3^{(1)}$
$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$	$\sum_j X_2^{(j)}$	$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$	$\sum_j X_3^{(j)}$		
$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$	$\sum_j X_3^{(j)}$							

Reduce-scatter

| Node |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| X_0 |
| X_1 |
| X_2 |
| X_3 |

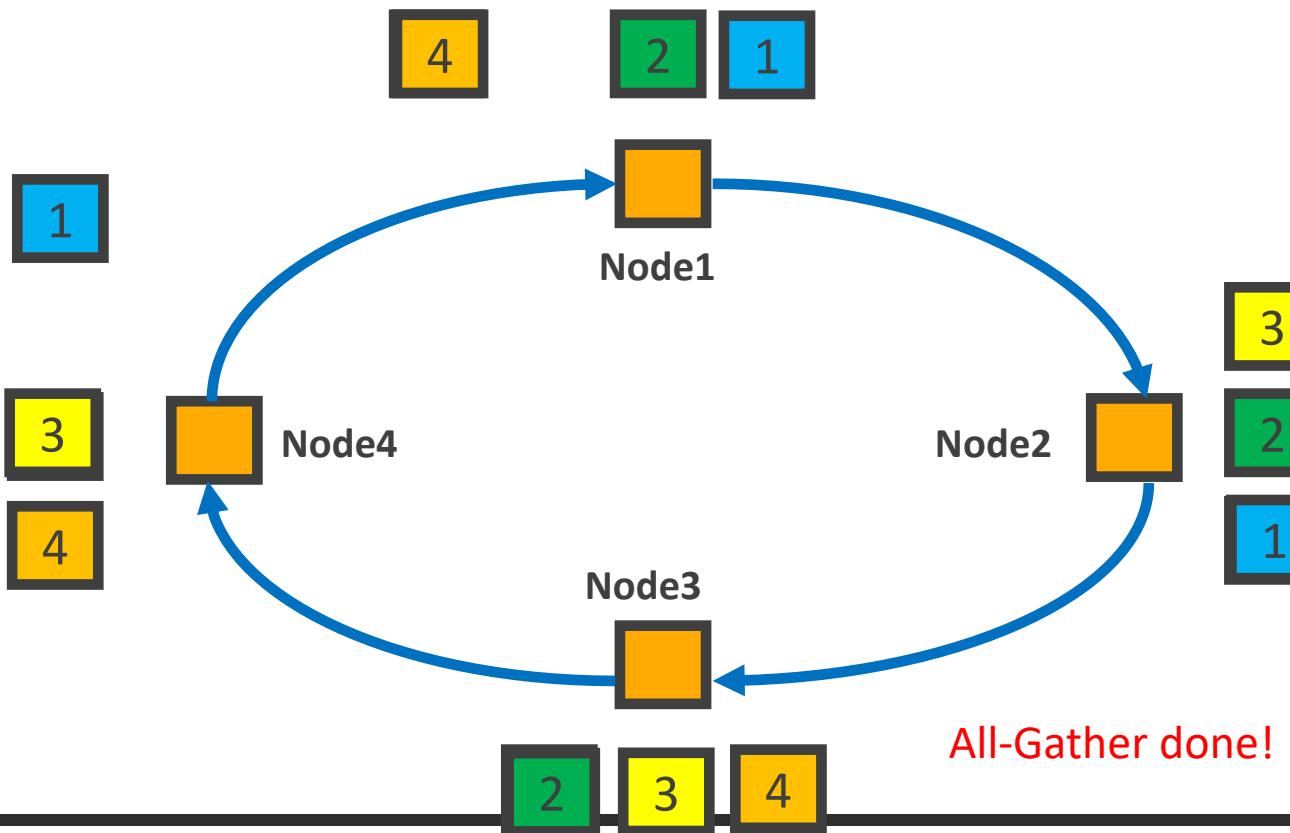
All-gather

Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$	$\sum_j X_0^{(j)}$	$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$	$\sum_j X_1^{(j)}$	$X_2^{(0)}$	$X_2^{(1)}$
$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$	$\sum_j X_1^{(j)}$	$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$	$\sum_j X_2^{(j)}$	$X_3^{(0)}$	$X_3^{(1)}$
$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$	$\sum_j X_2^{(j)}$	$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$	$\sum_j X_3^{(j)}$		
$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$	$\sum_j X_3^{(j)}$							

All-reduce

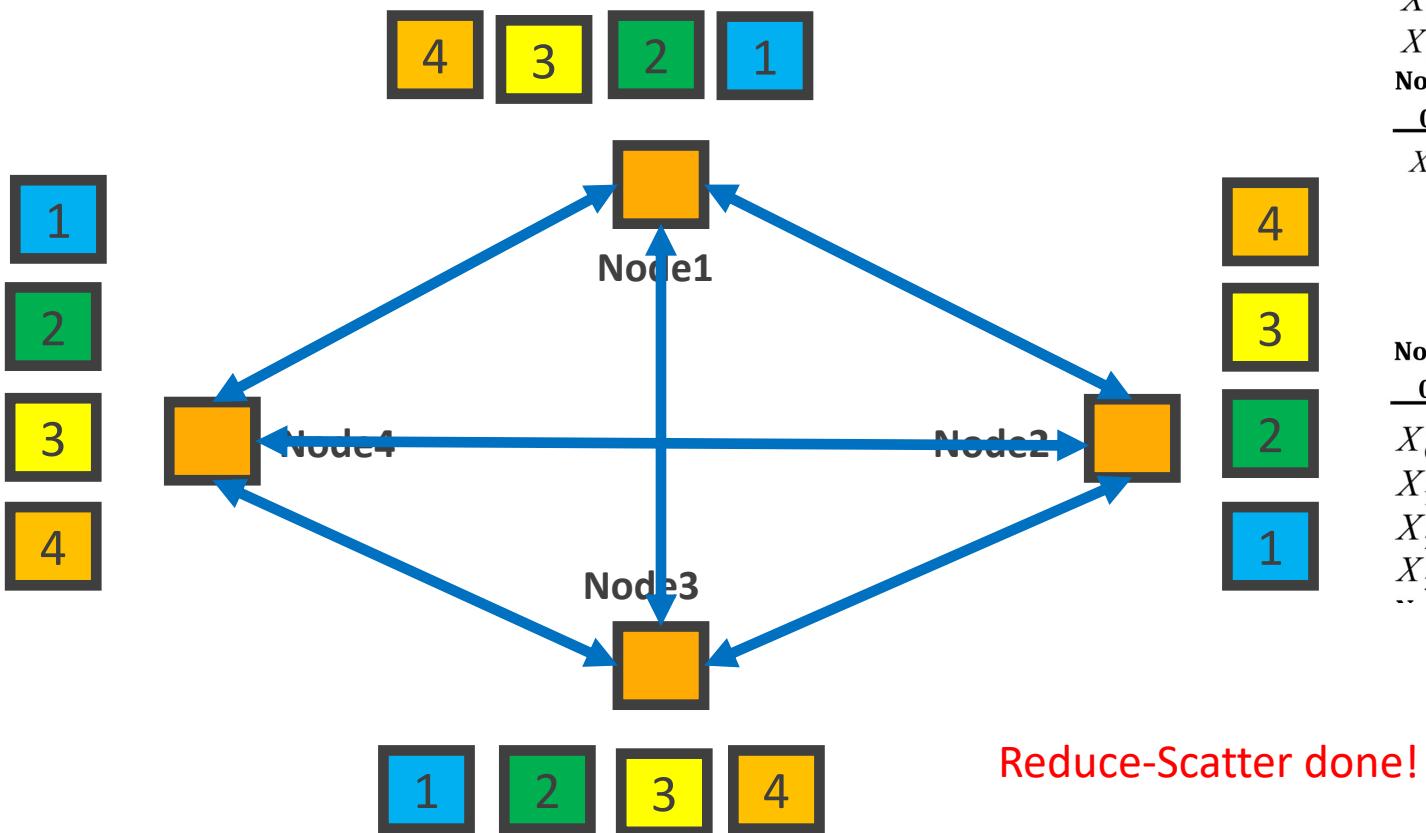
Example: Ring Based All-Reduce

- A ring with N nodes partitions data to N messages
- Collective Communication Flow:



Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3	0	1	2	3
$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$	$\sum_j X_0^{(j)}$							
$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$		$\sum_j X_1^{(j)}$						
$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$			$\sum_j X_2^{(j)}$					
$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$				$\sum_j X_3^{(j)}$				
Reduce -scatter											
Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3	0	1	2	3
X_0				X_0	X_0	X_0	X_0				
	X_1				X_1	X_1	X_1				
		X_2				X_2	X_2	X_2			
			X_3				X_3	X_3	X_3		
All-gather											
Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3	0	1	2	3
$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$	$\sum_j X_0^{(j)}$	$\sum_j X_0^{(j)}$	$\sum_j X_0^{(j)}$	$\sum_j X_0^{(j)}$				
$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$		$\sum_j X_1^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_1^{(j)}$			
$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$			$\sum_j X_2^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_2^{(j)}$		
$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$				$\sum_j X_3^{(j)}$	$\sum_j X_3^{(j)}$	$\sum_j X_3^{(j)}$	$\sum_j X_3^{(j)}$	
All-reduce											

Example: Direct All-Reduce



Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3	0	1	2	3
$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$	$\sum_j X_0^{(j)}$							
$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$		$\sum_j X_1^{(j)}$						
$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$			$\sum_j X_2^{(j)}$					
$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$				$\sum_j X_3^{(j)}$				

Reduce-scatter

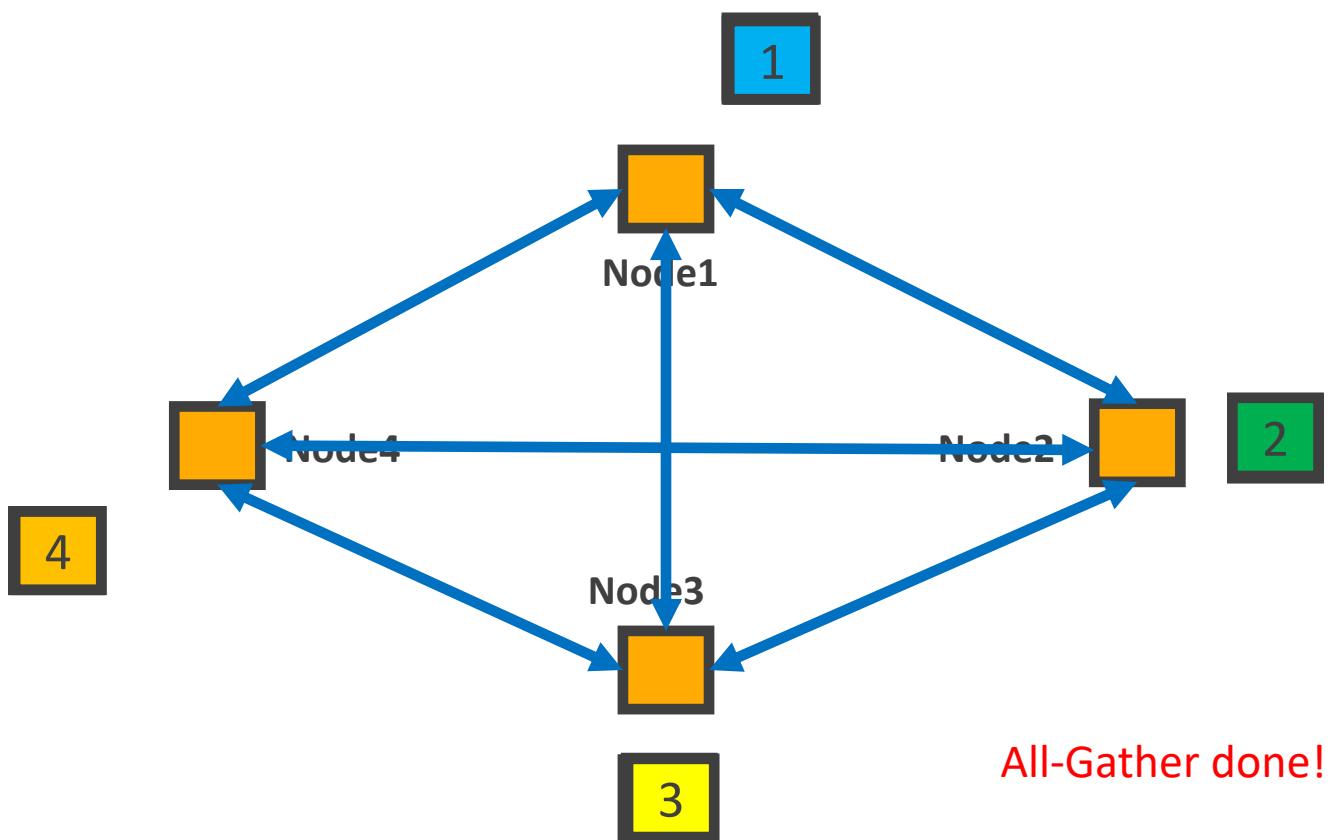
| Node |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0 | 1 | 2 | 3 | 0 | 1 | 2 | 3 | 0 | 1 | 2 | 3 |
| X_0 |
| X_1 |
| X_2 |
| X_3 |

All-gather

Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3	0	1	2	3
$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$	$\sum_j X_0^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_3^{(j)}$	$\sum_j X_0^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_3^{(j)}$
$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$		$\sum_j X_1^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_3^{(j)}$	$\sum_j X_0^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_3^{(j)}$
$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$			$\sum_j X_2^{(j)}$	$\sum_j X_3^{(j)}$	$\sum_j X_0^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_3^{(j)}$
$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$				$\sum_j X_3^{(j)}$	$\sum_j X_0^{(j)}$	$\sum_j X_1^{(j)}$	$\sum_j X_2^{(j)}$	$\sum_j X_3^{(j)}$

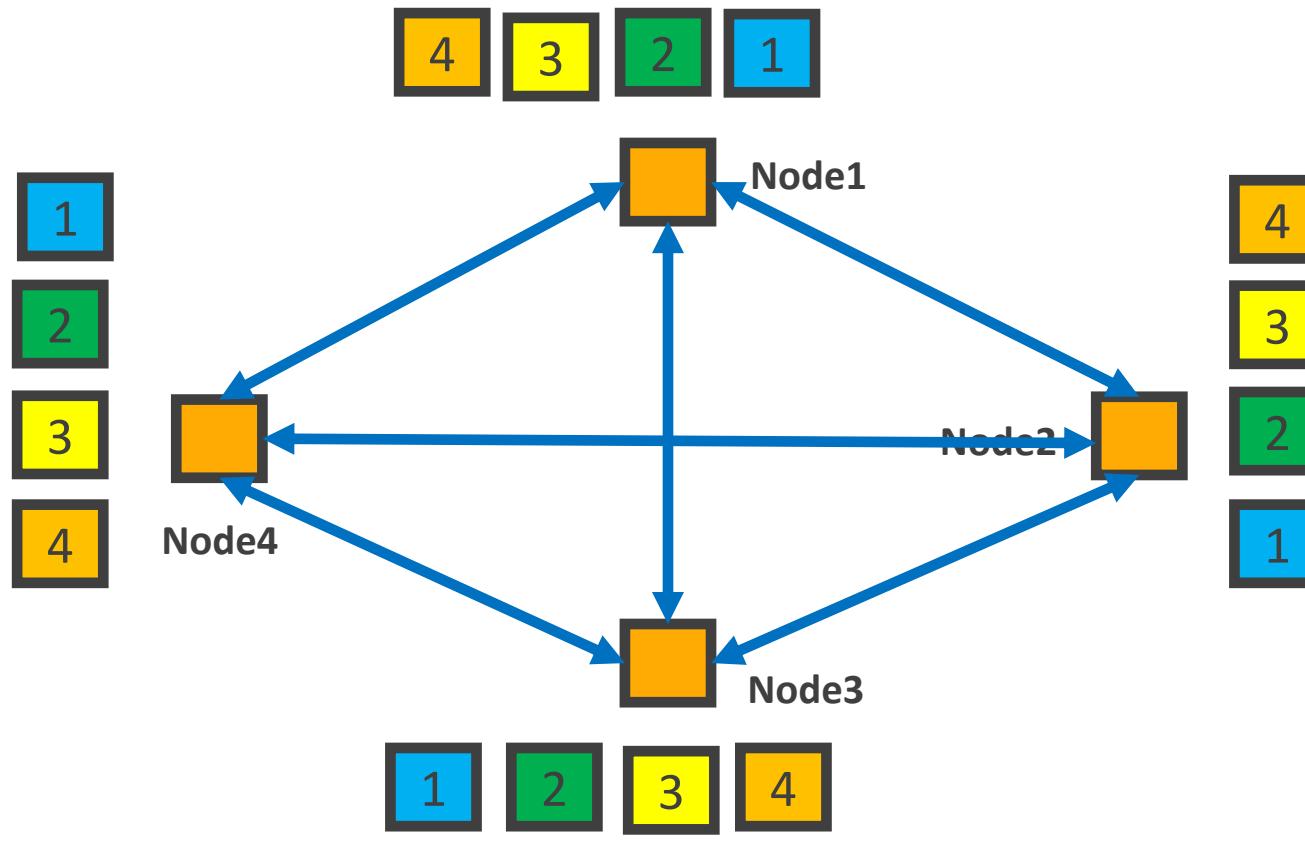
All-reduce

Example: Direct All-Reduce



Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3	0	1	2	3
$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$	$\sum_j X_0^{(j)}$				$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$
$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$	$\sum_j X_1^{(j)}$				$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$
$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$	$\sum_j X_2^{(j)}$				$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$
$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$	$\sum_j X_3^{(j)}$				$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$
				Reduce	-scatter						
Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3	0	1	2	3
X_0				X_0							
	X_1			X_1							
		X_2		X_2							
			X_3	X_3	X_3	X_3	X_3	X_3	X_3	X_3	X_3
				All-gather							
Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node	Node
0	1	2	3	0	1	2	3	0	1	2	3
$X_0^{(0)}$	$X_0^{(1)}$	$X_0^{(2)}$	$X_0^{(3)}$	$\sum_j X_0^{(j)}$							
$X_1^{(0)}$	$X_1^{(1)}$	$X_1^{(2)}$	$X_1^{(3)}$	$\sum_j X_1^{(j)}$							
$X_2^{(0)}$	$X_2^{(1)}$	$X_2^{(2)}$	$X_2^{(3)}$	$\sum_j X_2^{(j)}$							
$X_3^{(0)}$	$X_3^{(1)}$	$X_3^{(2)}$	$X_3^{(3)}$	$\sum_j X_3^{(j)}$							
				All-reduce							

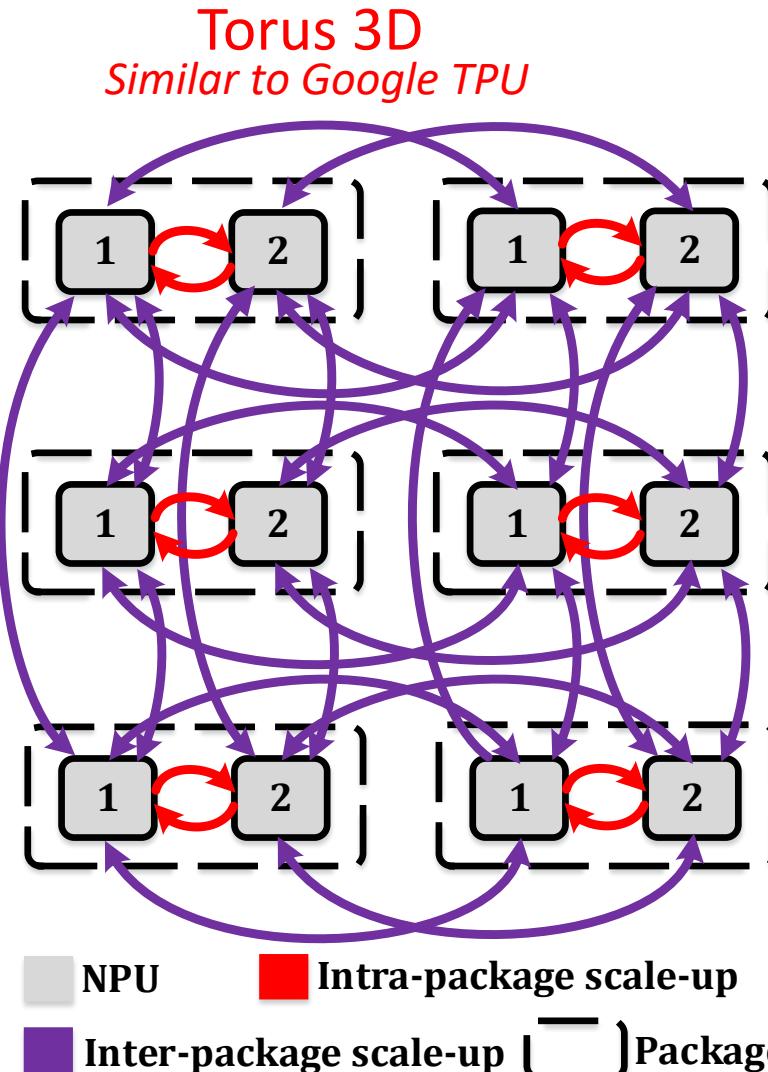
Example: All-to-All



| Node |
|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 0 | 1 | 2 | 3 | 0 | 1 | 2 | 3 |
| $X_0^{(0)}$ | $X_0^{(1)}$ | $X_0^{(2)}$ | $X_0^{(3)}$ | $X_0^{(0)}$ | $X_1^{(0)}$ | $X_2^{(0)}$ | $X_3^{(0)}$ |
| $X_1^{(0)}$ | $X_1^{(1)}$ | $X_1^{(2)}$ | $X_1^{(3)}$ | $X_0^{(1)}$ | $X_1^{(1)}$ | $X_2^{(1)}$ | $X_3^{(1)}$ |
| $X_2^{(0)}$ | $X_2^{(1)}$ | $X_2^{(2)}$ | $X_2^{(3)}$ | $X_0^{(2)}$ | $X_1^{(2)}$ | $X_2^{(2)}$ | $X_3^{(2)}$ |
| $X_3^{(0)}$ | $X_3^{(1)}$ | $X_3^{(2)}$ | $X_3^{(3)}$ | $X_0^{(3)}$ | $X_1^{(3)}$ | $X_2^{(3)}$ | $X_3^{(3)}$ |

All-to-all

Collectives on Sophisticated Training Platforms



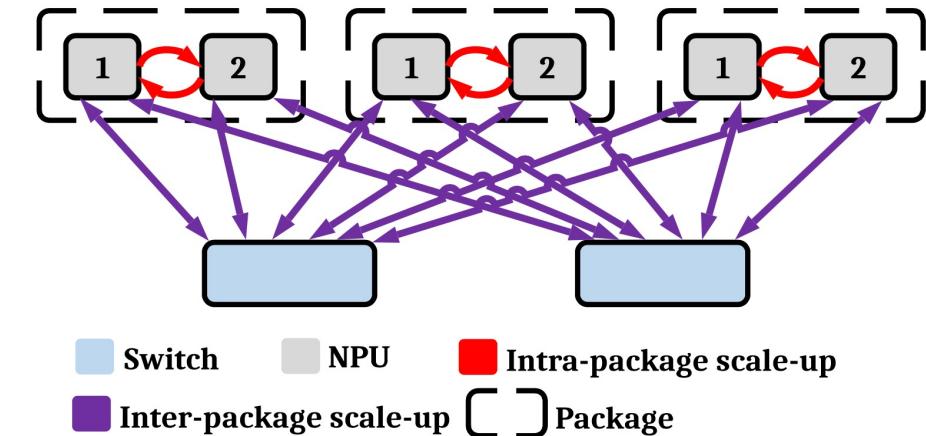
Hierarchical all-reduce:

- Reduce-scatter **within package**
- All-reduce across rows
- All-reduce across columns
- All-gather **within package**

Heterogeneous Bandwidth

Multi-phase Collectives

All-To-All
Similar to NVIDIA DGX2



Hierarchical all-reduce:

- Reduce-scatter **within package**
- All-reduce across switch
- All-gather **within package**

Systems challenges with Distributed Training

- Communication!
 - Inevitable in any distributed algorithm
- What does communication depend on?
 - **synchronization scheme:** synchronous vs. asynchronous.
 - **parallelism approach:** data-parallel, model-parallel, hybrid-parallel., ZeRO ...
- Is it a problem?
 - Depends ... can we hide it behind compute?
 - *How do we determine this?*

Understanding DL Training design-space

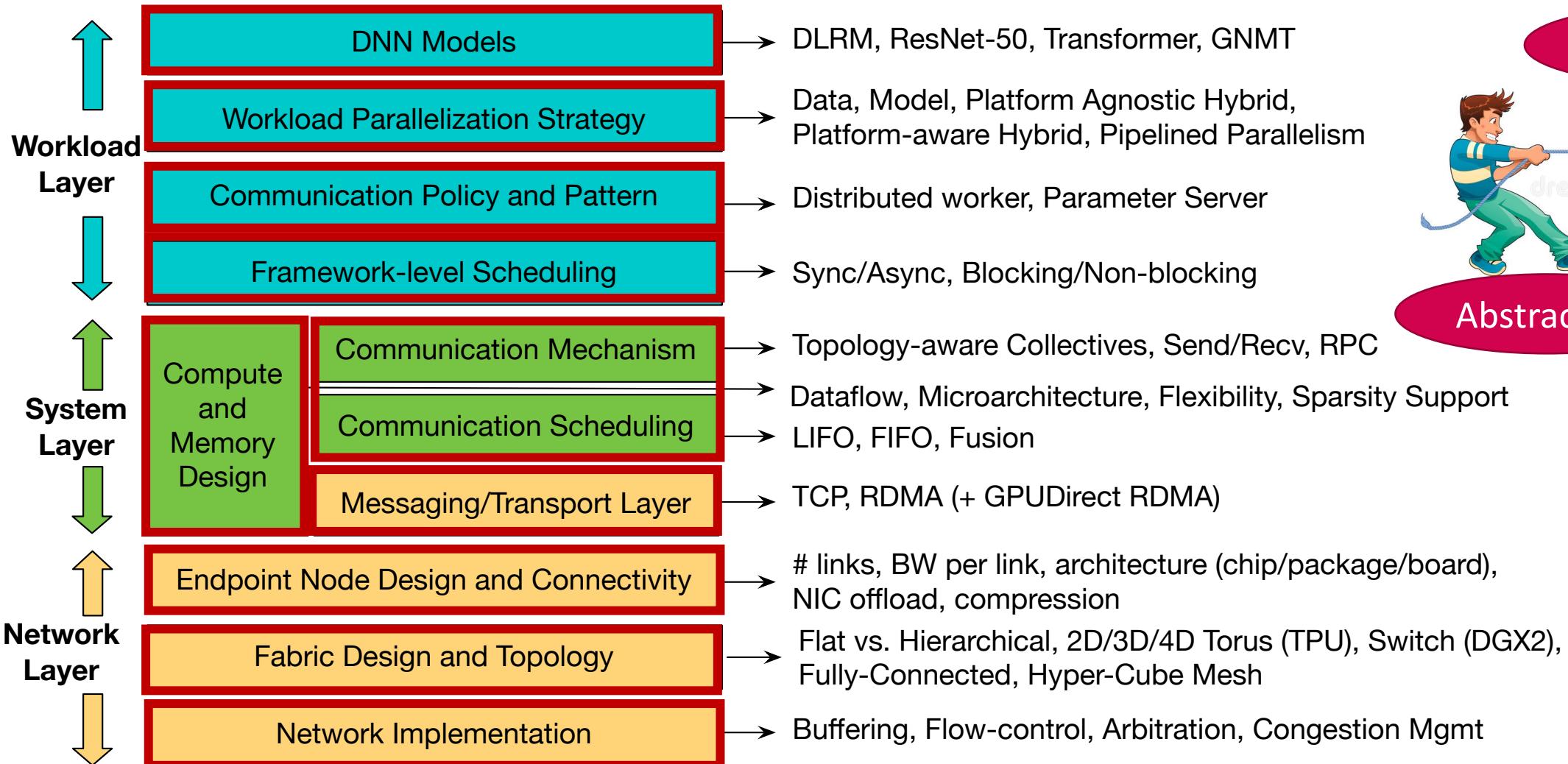


Figure Courtesy: Srinivas Sridharan (Facebook)

Distributed Training Stack

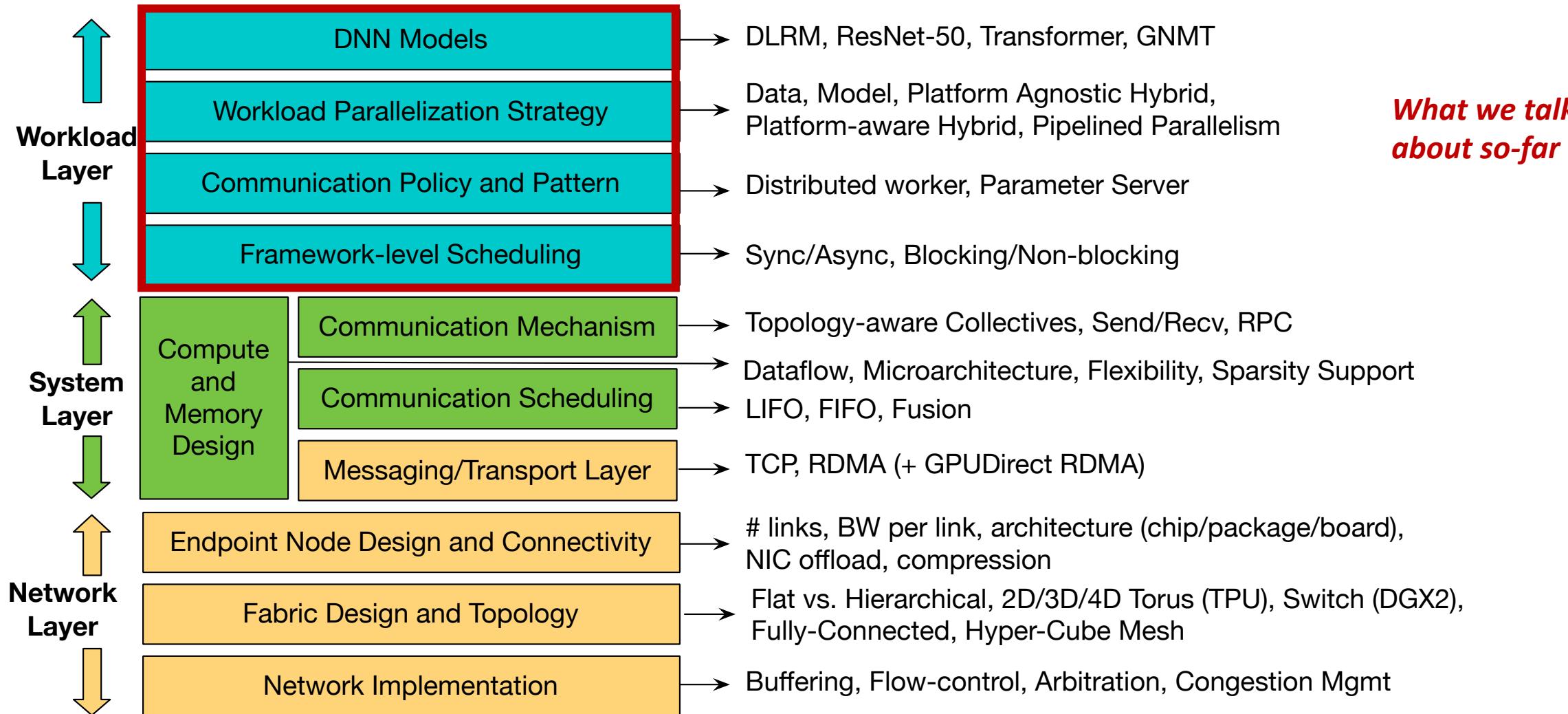


Figure Courtesy: Srinivas Sridharan (Facebook)

Distributed Training Stack

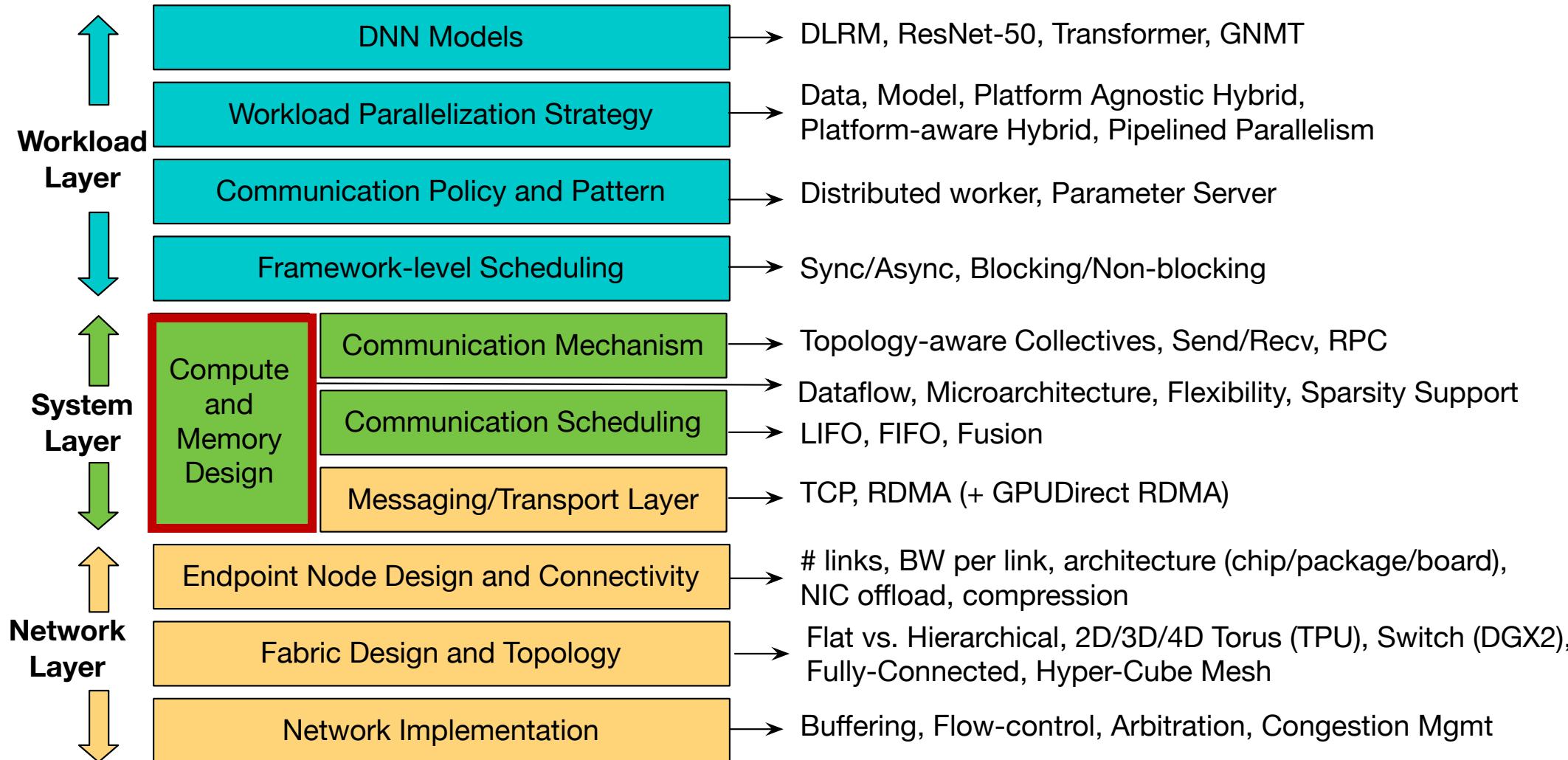
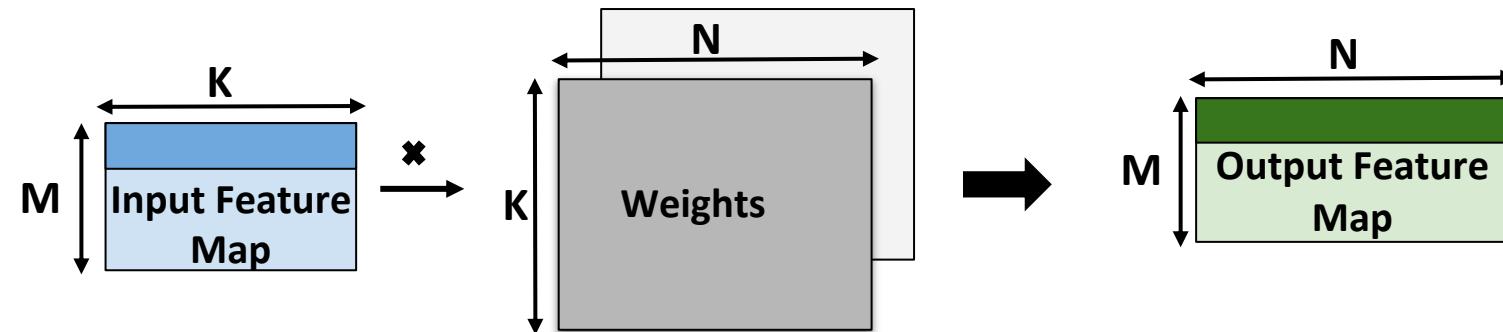


Figure Courtesy: Srinivas Sridharan (Facebook)

DL Training: The Compute

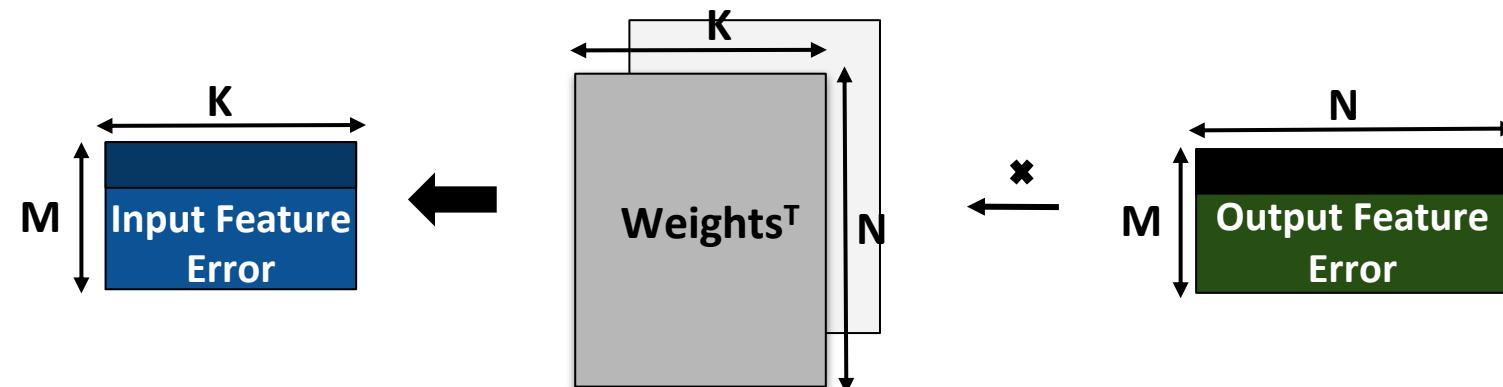
Forward Pass (Inference and Training)



GEMM MNK Dimension Representation

M dim: batch size

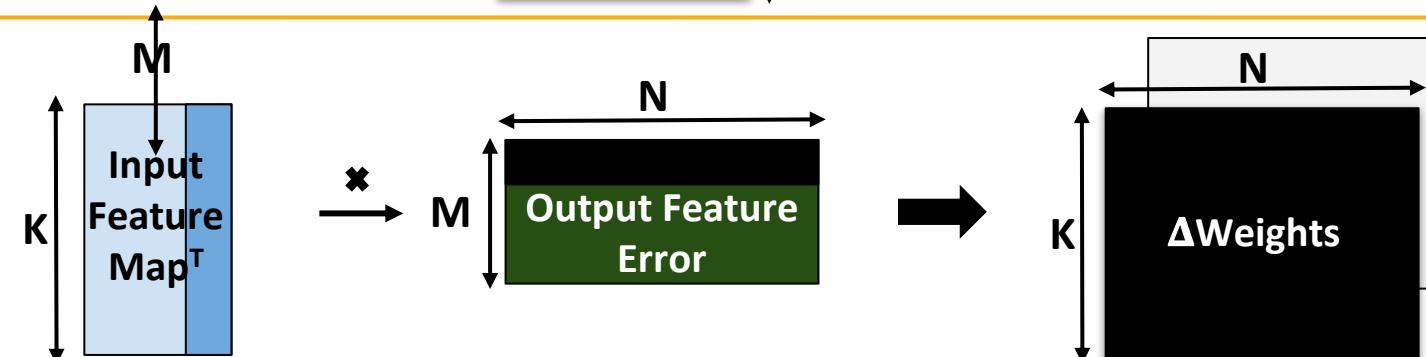
Backward Pass (Training)



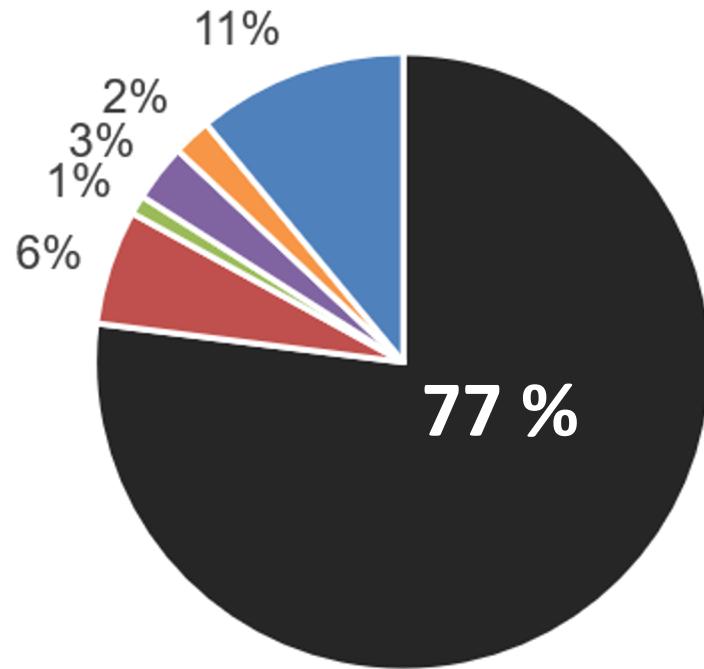
N dim: number of channels in the next layer

K dim: [H * W * C]

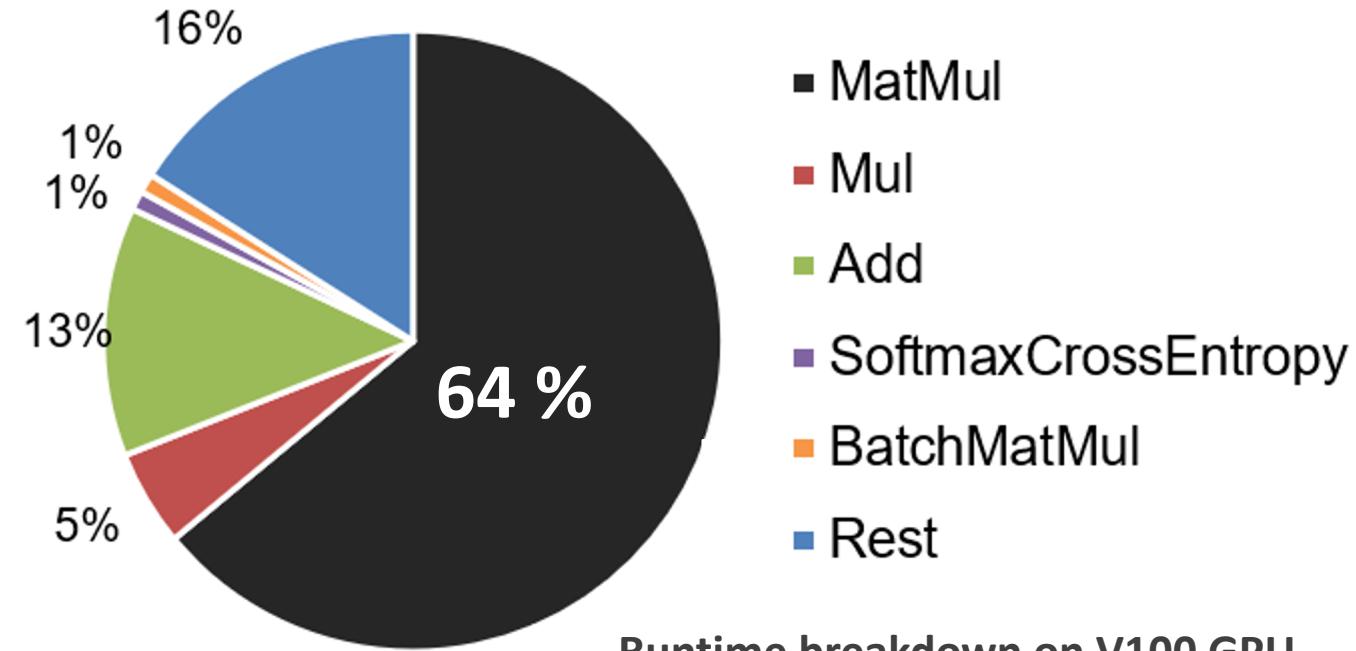
Gradient Computation (Training)



Key Compute Kernel during DL Training



Transformer
(Language Understanding)



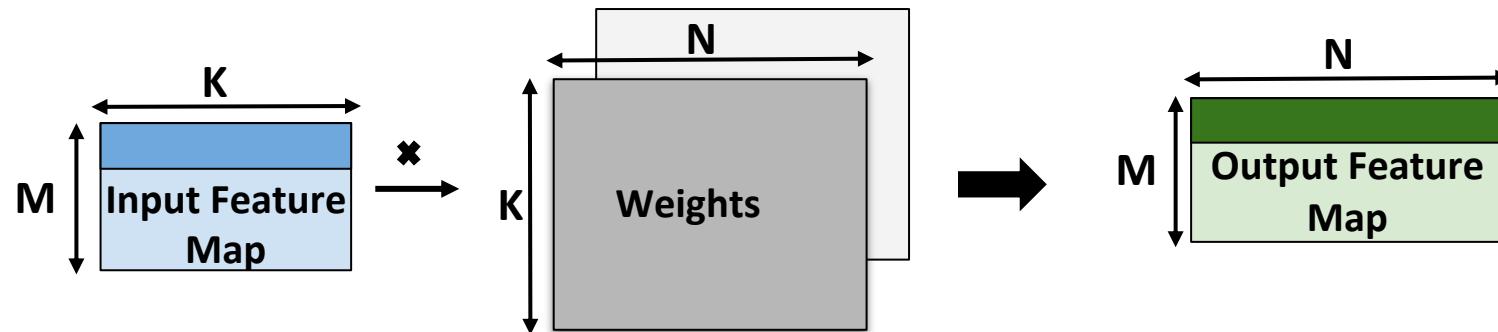
GNMT
(Machine Translation)

Runtime breakdown on V100 GPU

Matrix multiplications (GEMMs) consume around **70%** of the total runtime when training modern deep learning workloads.

GEMMs in Deep Learning

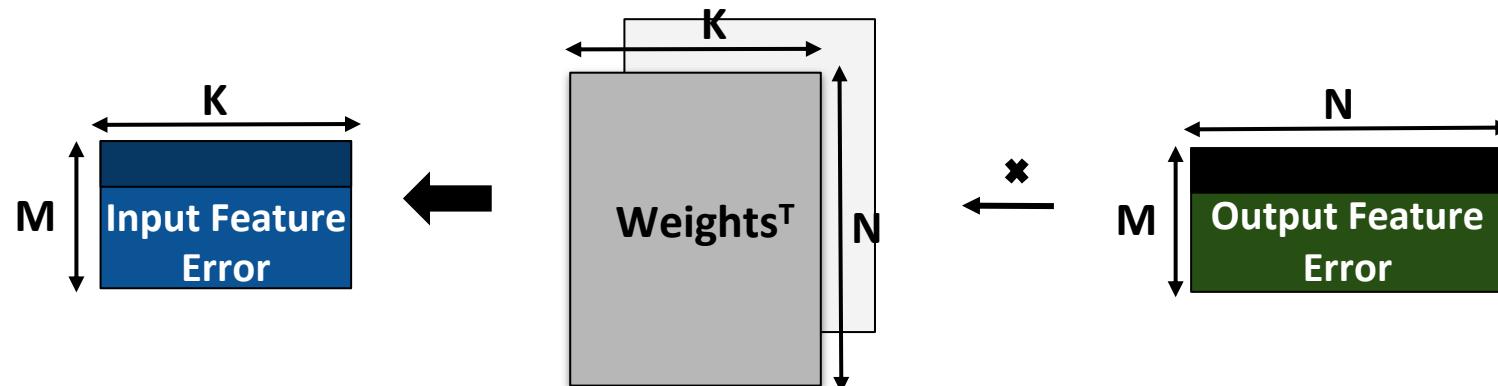
Forward Pass (Inference and Training)



GEMM MNK
Dimension Representation

M dim: batch size

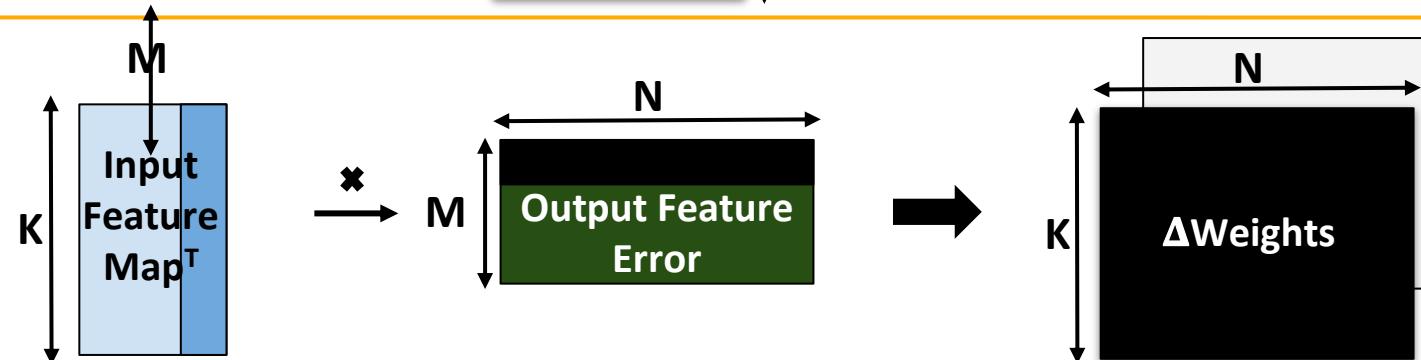
Backward Pass (Training)



N dim: number of channels in the next layer

K dim: [H * W * C]

Gradient Computation (Training)

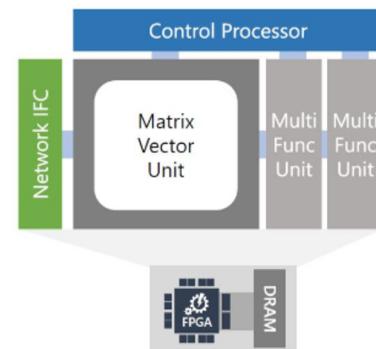


Hardware for Accelerating GEMMs

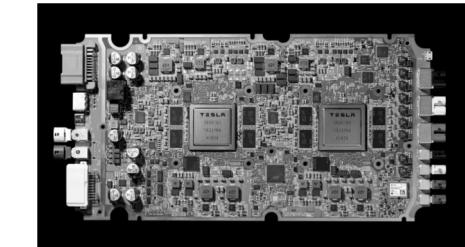
SIMT Architectures



Nvidia GTX GPUs

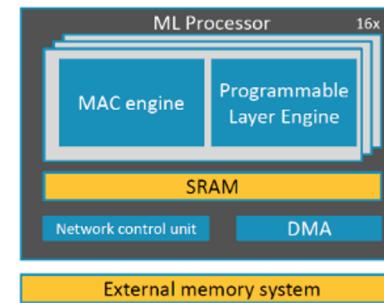


Microsoft Brainwave



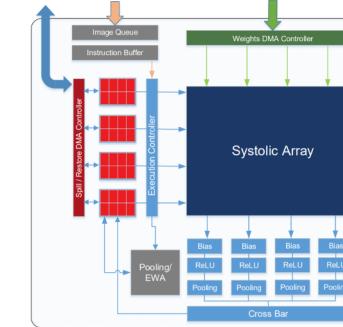
Tesla FSDC

SIMD Architectures

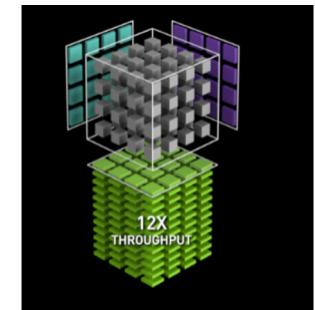


ARM Trillium

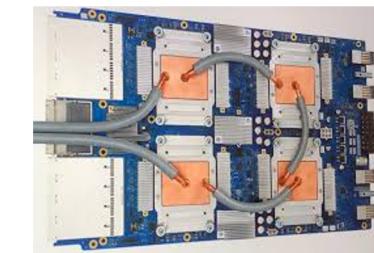
Systolic Architectures



Xilinx xDNN



Nvidia Tensor Cores



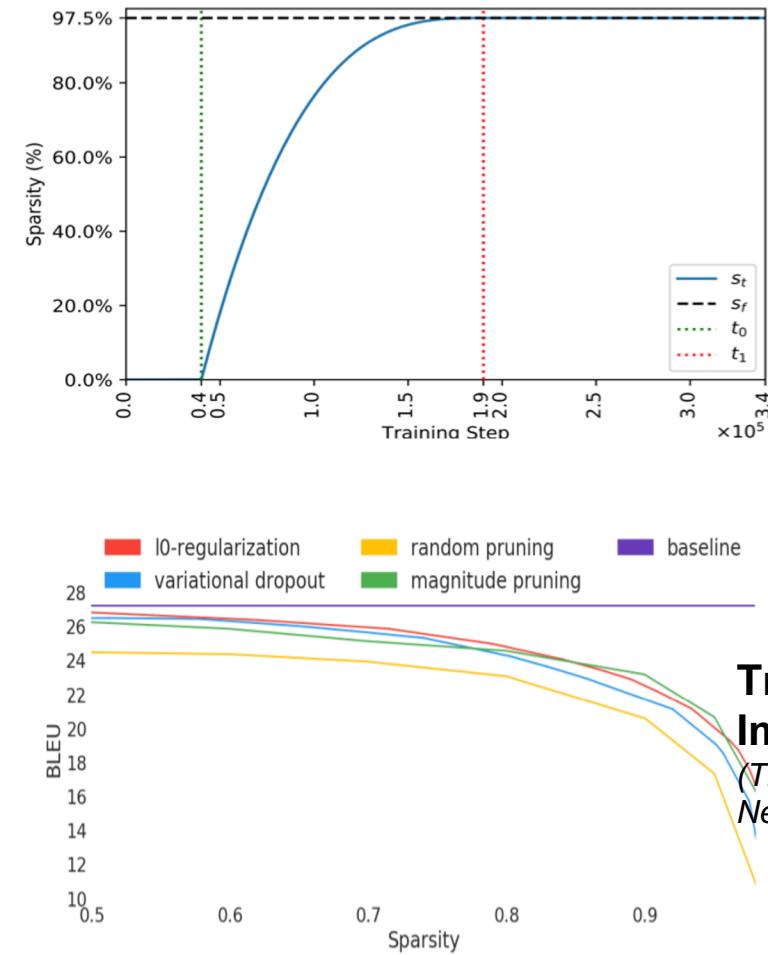
Google TPU

Key Feature: Specialized support for GEMMs

GEMMs in Modern DL

Workload	Application	Example Dimensions		
		M	N	K
GNMT	Machine Translation	128	2048	4096
		320	3072	4096
		1632	36548	1024
		2048	4096	32
DeepBench	General Workload	1024	16	500000
		35	8457	2560
Transformer	Language Understanding	31999	1024	84
		84	1024	4096
NCF	Collaborative Filtering	2048	1	128
		256	256	2048

GEMMs are irregular (non-square)!

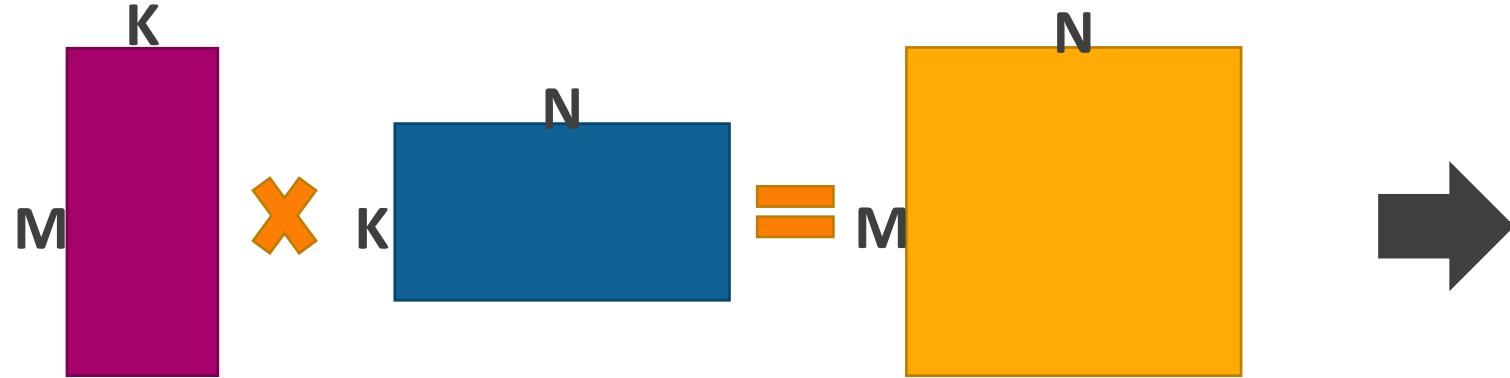


GNMT Pruning - Temporal Sparsity
(<https://www.intel.ai/compressing-gnmt-models>)

Transformer Sparsity - Impact on BLEU
(The State of Sparsity in Deep Neural Networks, Gale et al., arXiv)

GEMMs are Sparse! Weight sparsity ranges from 40% to 90%. Activation sparsity is approximately 30% to 70% from ReLU, dropout, etc.

Mapping GEMMs on to TPU



What determines *utilization*?

Mapping Efficiency

What determines *stalls*?

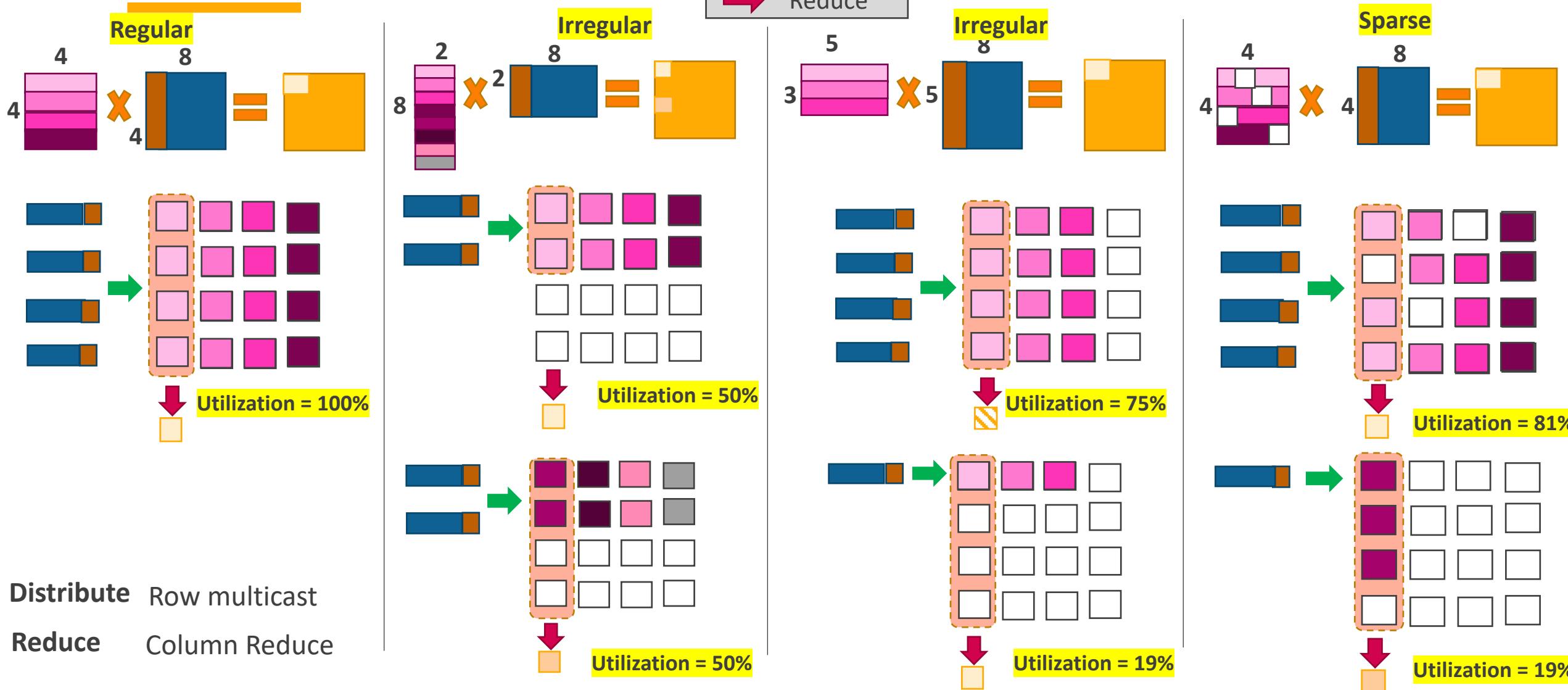
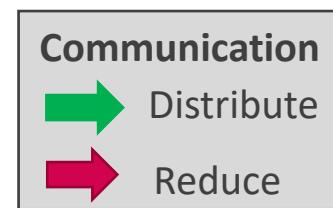
Memory/Interconnect Bandwidth

TPU (Systolic Array)

0	15 ..	31 ..	47 ..	63 ..	79 ..	95 ..	111 ..	127
15								
.								
31								
.								
47								
.								
63								
.								
79								
.								
95								
.								
111								
.								
127								

**** Assuming MK matrix is streaming and KN matrix is stationary. (aka weight stationary)**

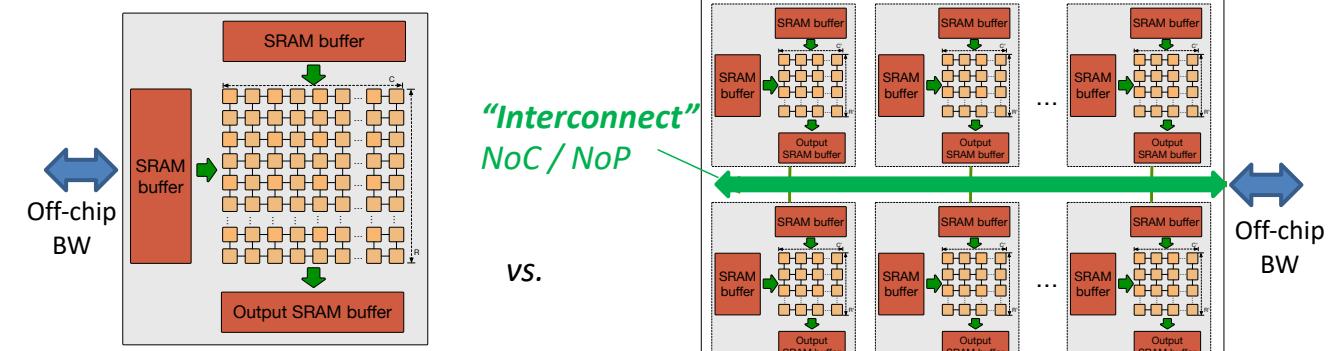
Mapping Examples



Mechanisms to increase utilization

- **Handling Irregular GEMMs**

- One large array (e.g., Google TPU) versus several smaller arrays (e.g., NVIDIA Tensor cores)
 - Trade-off: reuse vs utilization

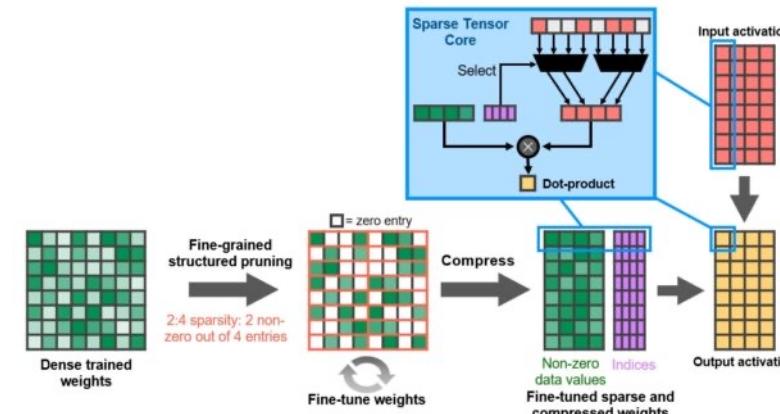


- **Handling Sparse GEMMs**

- Structured Sparsity Support

- E.g., NVIDIA A100

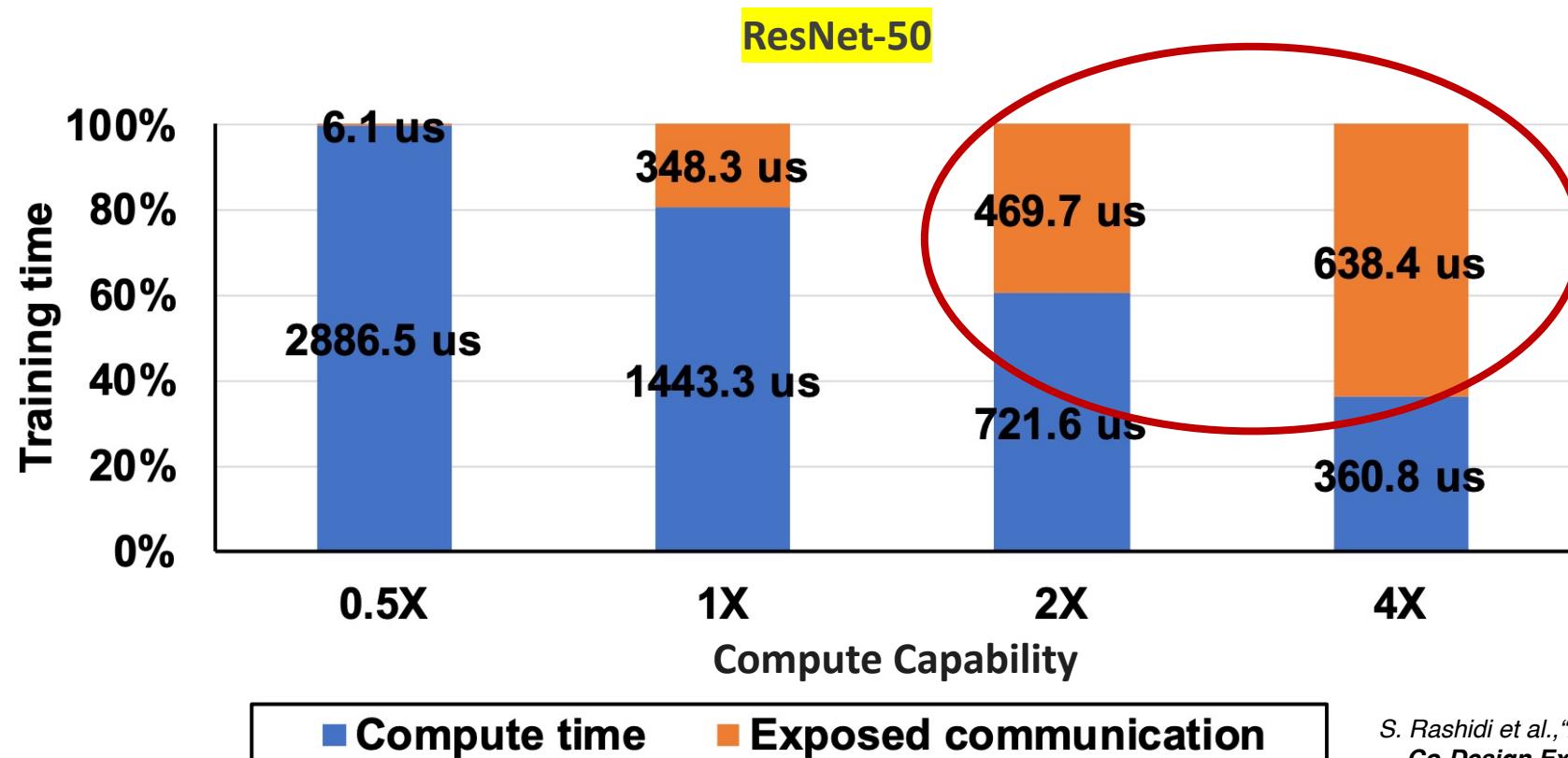
- Unstructured Sparsity Support
 - Active research going on



NVIDIA A100 supports 4:2 structured sparsity

Effect of Enhanced Compute Efficiency on Training

- A Torus 3D with total of 32 nodes (2X4X4) is used.



S. Rashidi et al., "ASTRA-SIM: Enabling SW/HW Co-Design Exploration for Distributed DL Training Platforms", ISPASS 2020

Distributed Training Stack

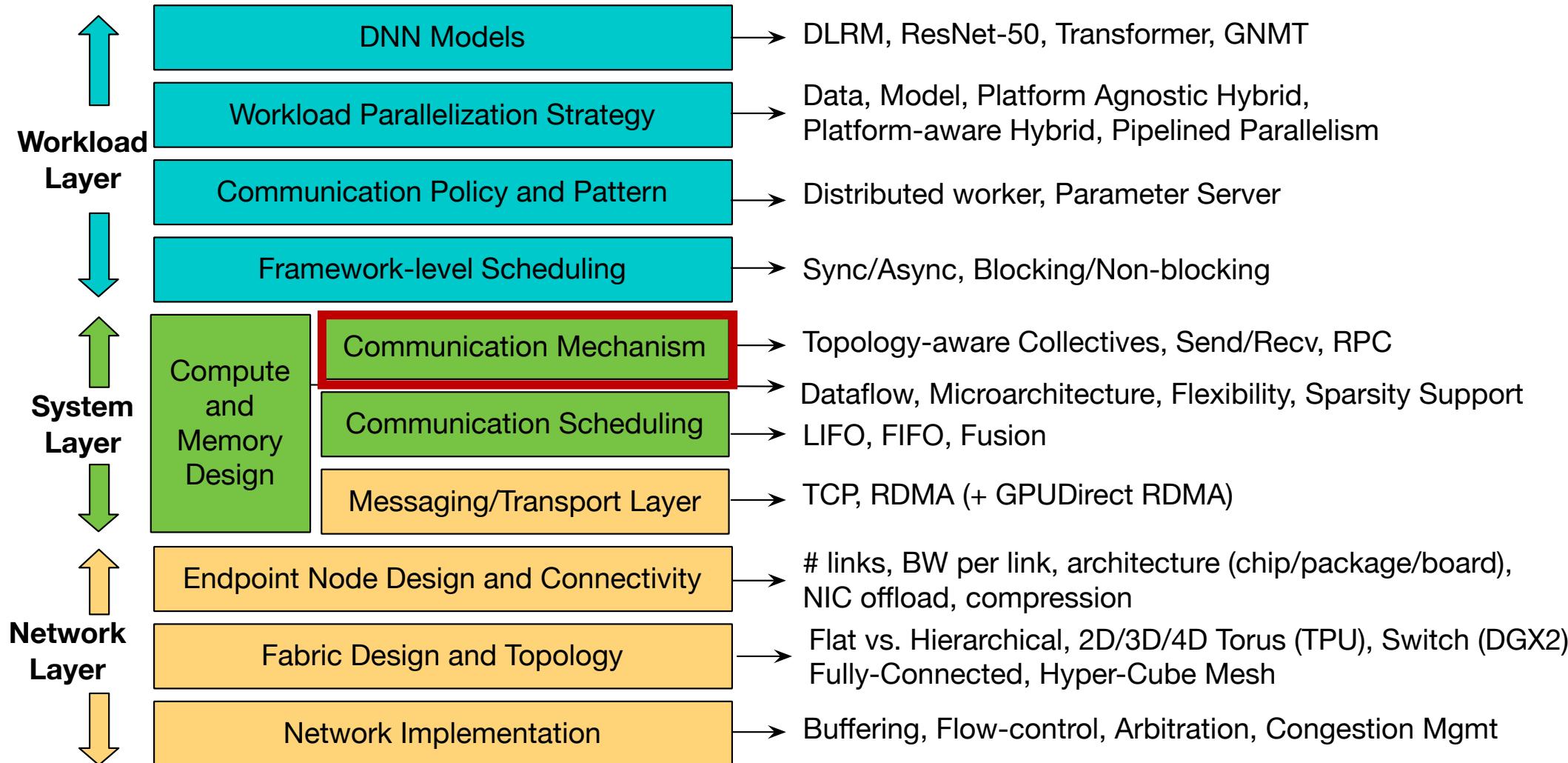
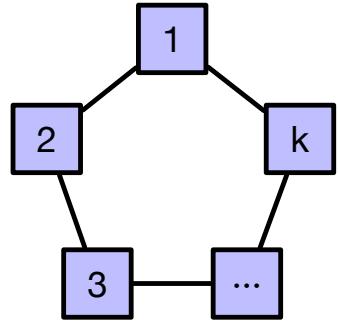
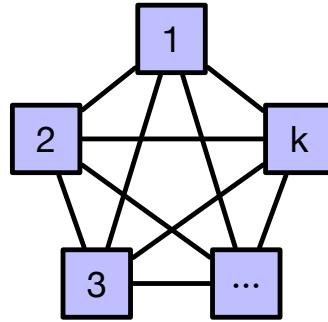
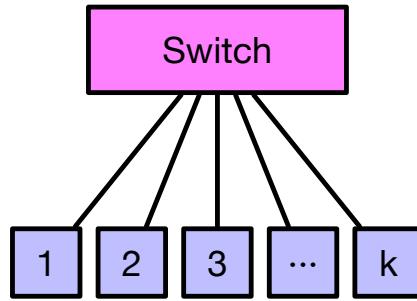
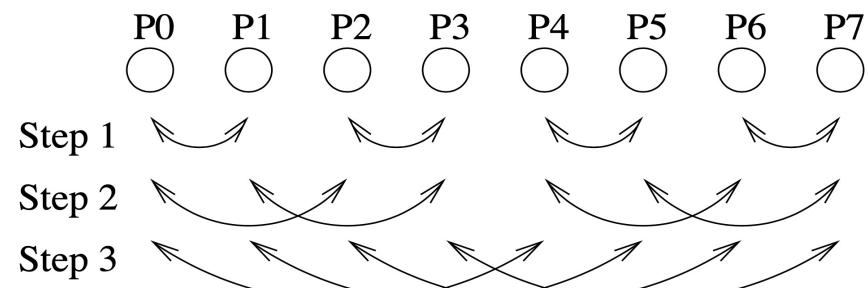


Figure Courtesy: Srinivas Sridharan (Facebook)

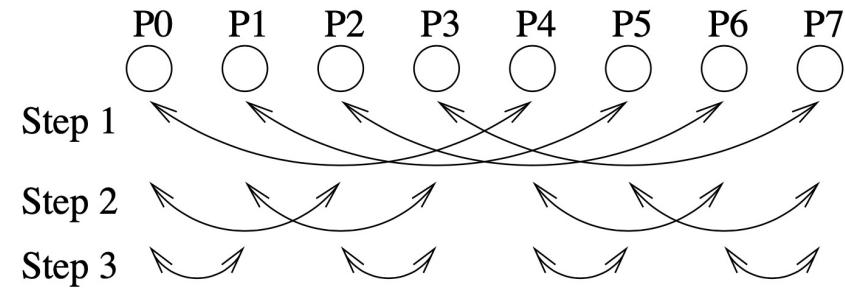
Topology-aware Collectives

(a) Ring(k)(b) FullyConnected(k)(b) Switch(k)

Topology Building Block	Topology-aware Collective Algorithm
Ring	Ring
FullyConnected	Direct
Switch	HalvingDoubling



a) Reduce-Scatter phases



b) All-gather phases

HalvingDoubling All-Reduce

Distributed Training Stack

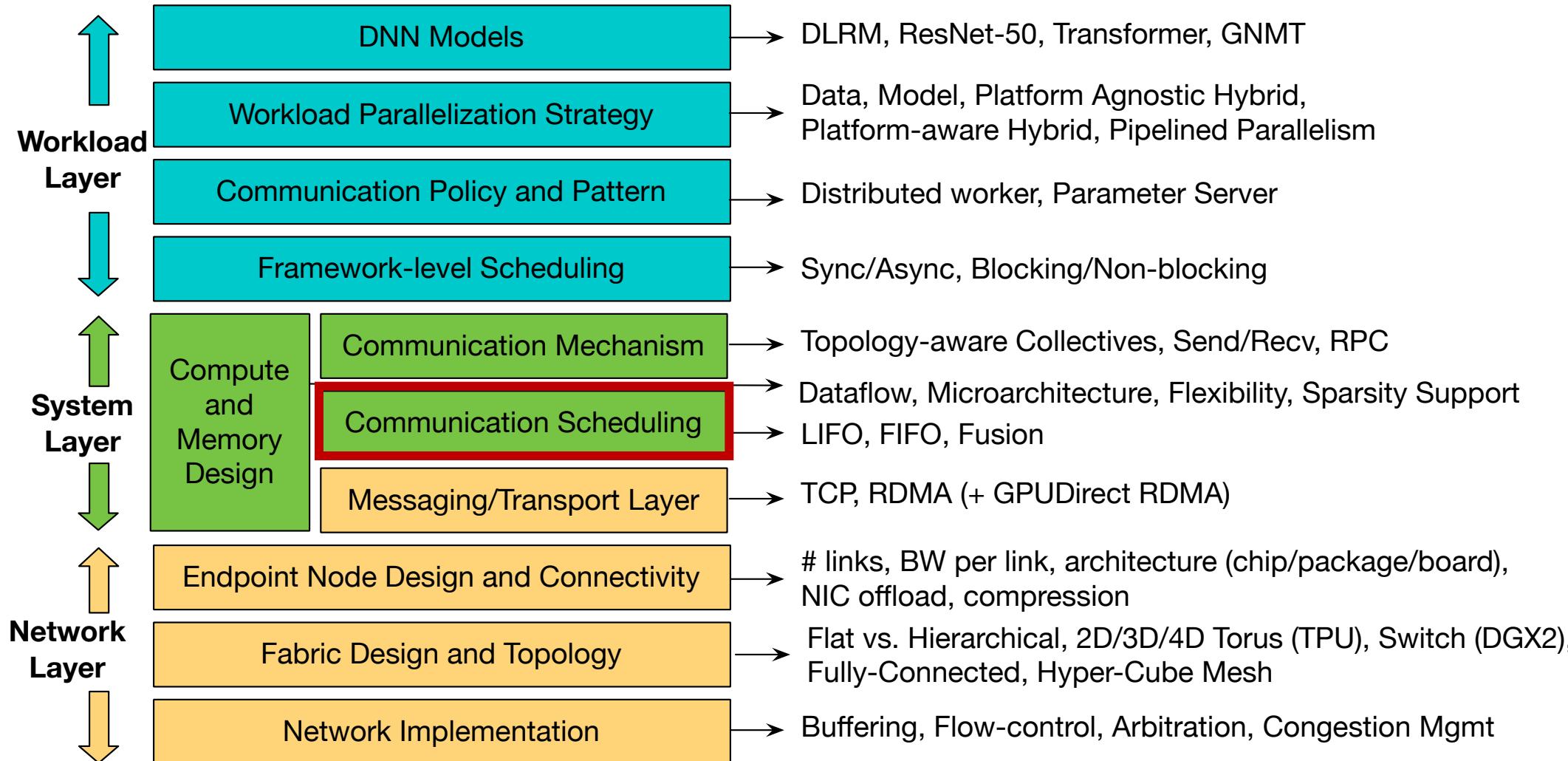
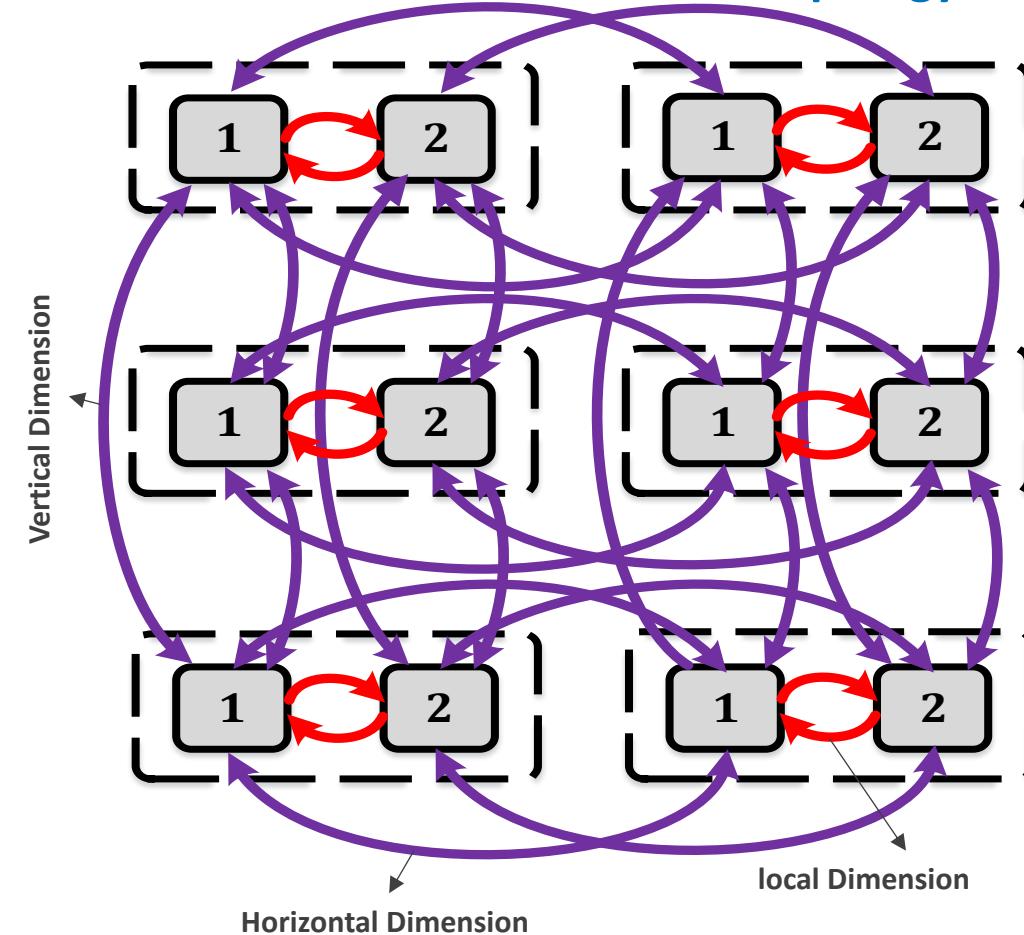


Figure Courtesy: Srinivas Sridharan (Facebook)

Baseline All-Reduce on the Hierarchical Topologies

3D Torus – Hierarchical Topology

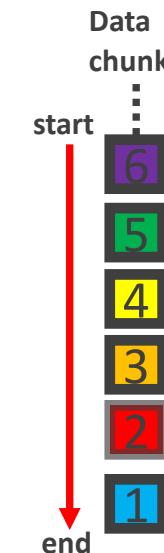
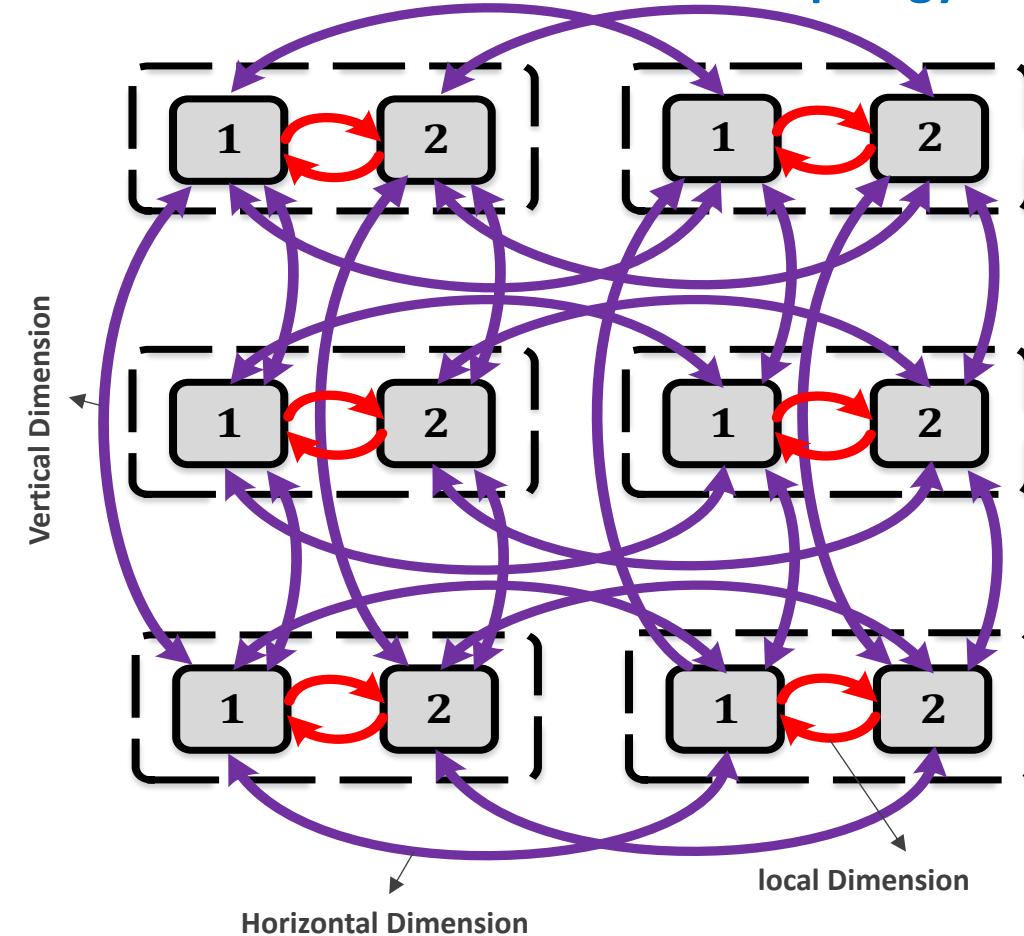


Data chunks	All-reduce pipeline on the hierarchical topologies:	Suppose the chunk size per NPU is initially 12MB
start	Step:	Chunk size in the initial of the phase:
6	1. Reduce-scatter on the local dimension	12MB
5	2. Reduce-scatter on the horizontal dimension	6MB
4	3. Reduce-scatter on the vertical dimension	3MB
3	4. All-gather on the vertical dimension	1MB
2	5. All-gather on the horizontal dimension	3MB
1	6. All-gather on the local dimension	6MB
		End: 12MB

S. Rashidi et al., "Themis: A Network Bandwidth-Aware Collective Scheduling Policy for Distributed Training of DL Models". arXiv preprint.

Baseline All-Reduce on the Hierarchical Topologies

3D Torus – Hierarchical Topology

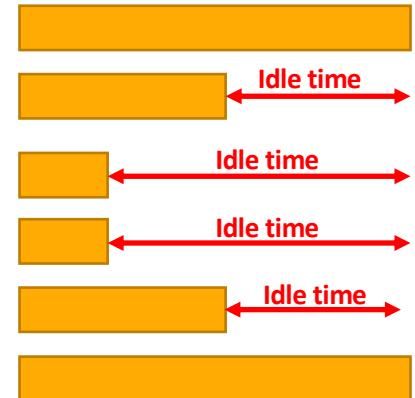


Step:

1. Reduce-scatter on the **local dimension**
2. Reduce-scatter on the **horizontal dimension**
3. Reduce-scatter on the **vertical dimension**
4. All-gather on the **vertical dimension**
5. All-gather on the **horizontal dimension**
6. All-gather on the **local dimension**

All-reduce pipeline on the hierarchical topologies:

Pipeline Stage latency:



Problem: Uneven pipeline stage latencies that causes network underutilization

S. Rashidi et al., "Themis: A Network Bandwidth-Aware Collective Scheduling Policy for Distributed Training of DL Models". arXiv preprint.

Distributed Training Stack

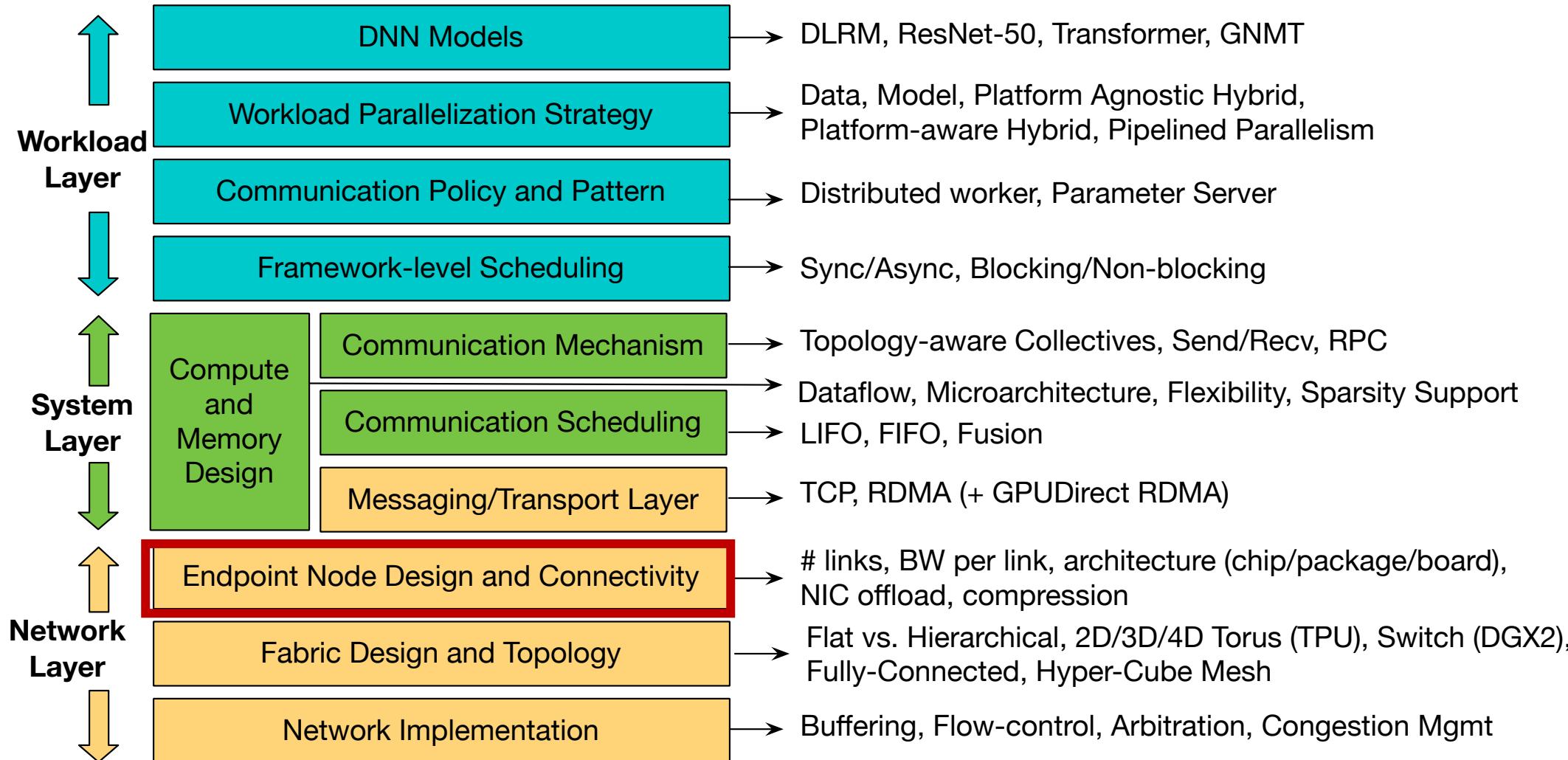
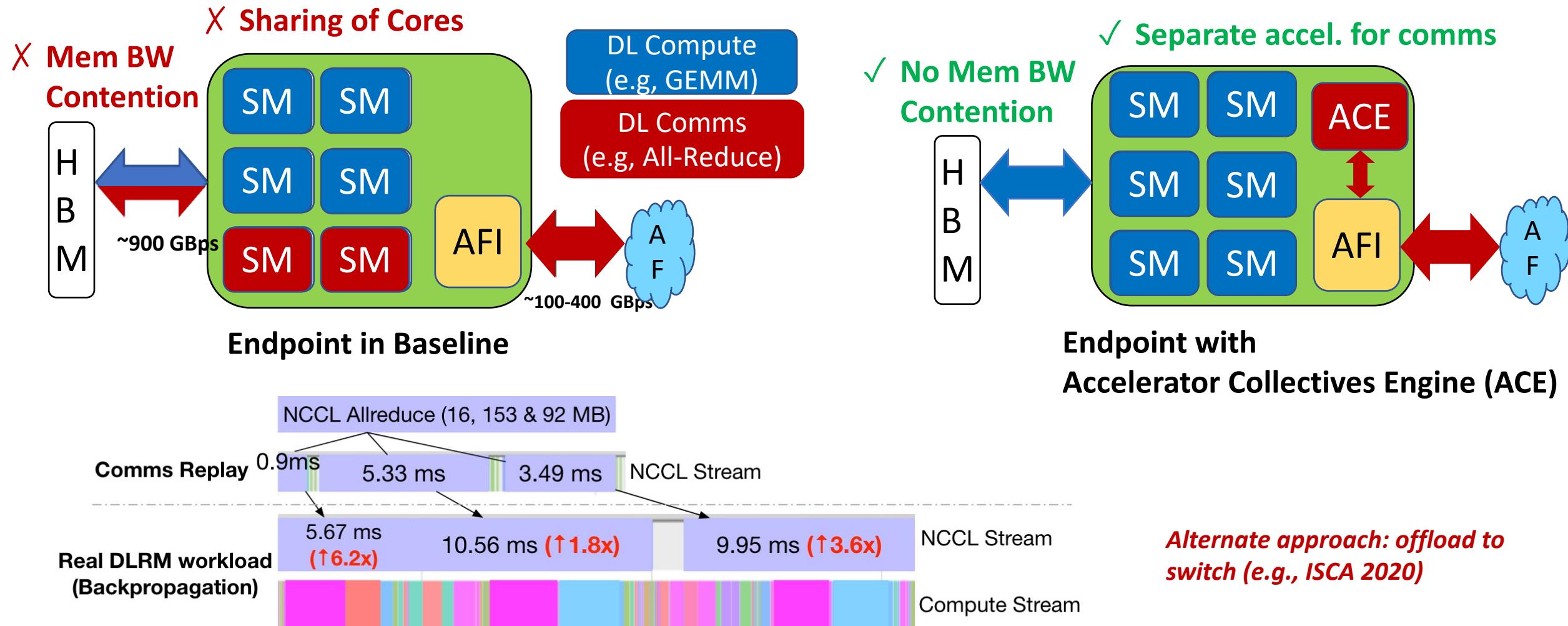


Figure Courtesy: Srinivas Sridharan (Facebook)

Resource Contention at End-point



(b) Impact of compute-comms overlap on a real-world production-class DLRM workload

S. Rashidi et al., "Enabling Compute-Communication Overlap in Distributed Deep Learning Training Platforms". ISCA 2021

Distributed Training Stack

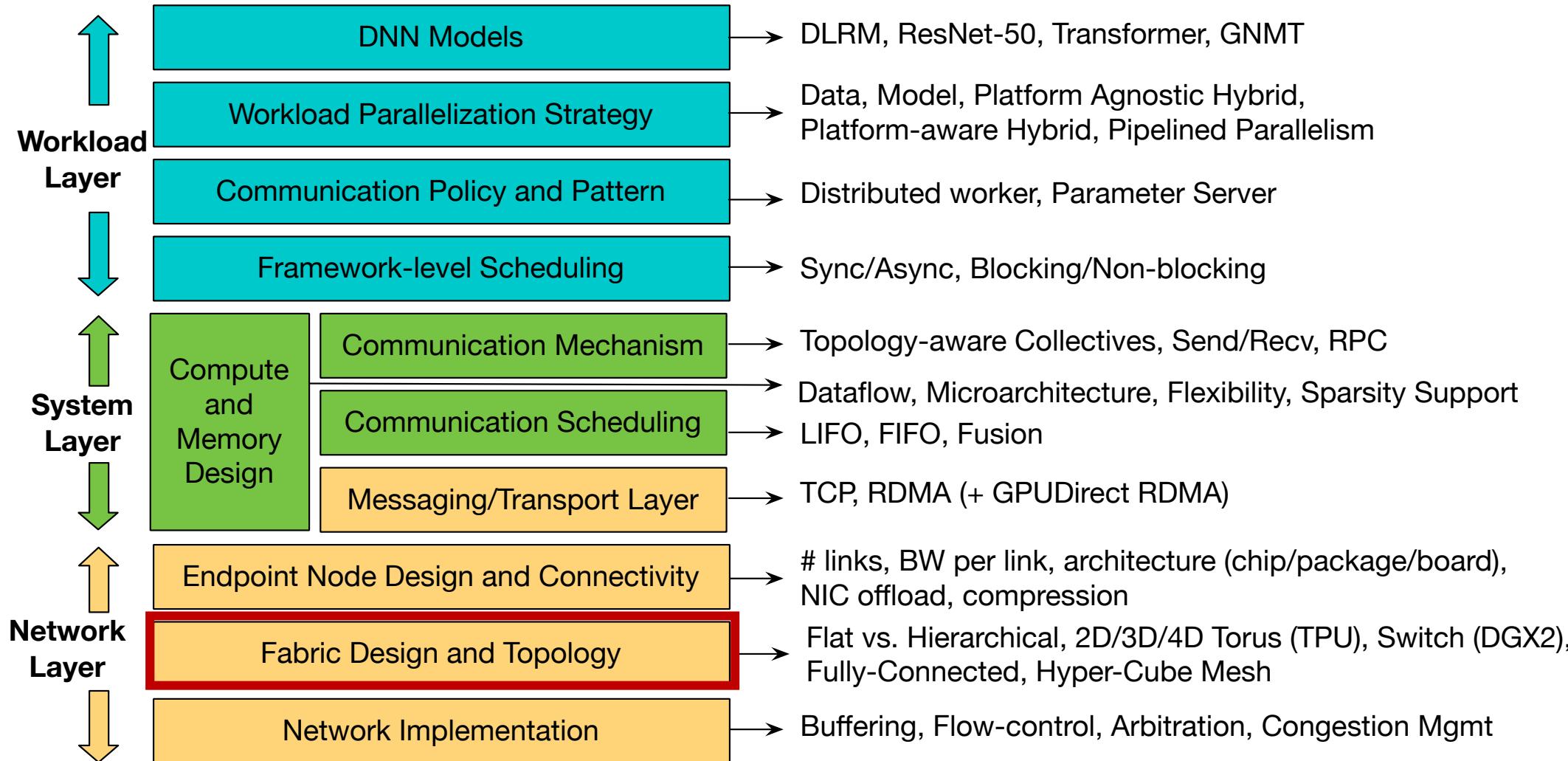
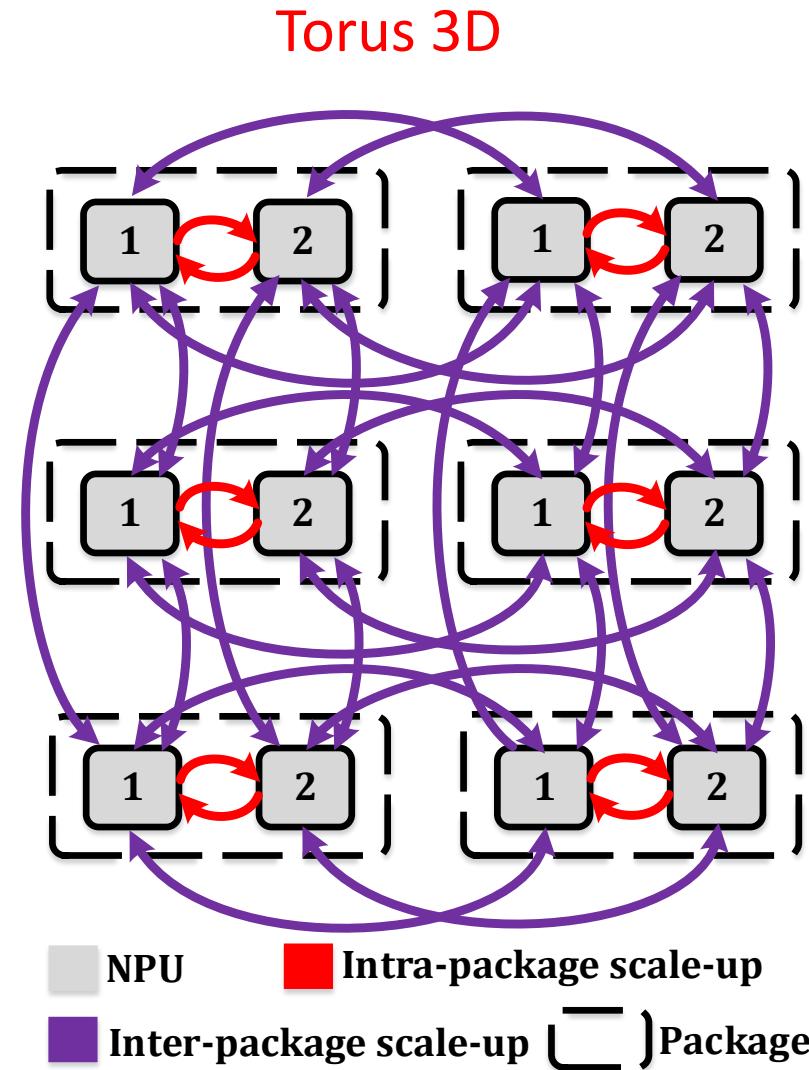


Figure Courtesy: Srinivas Sridharan (Facebook)

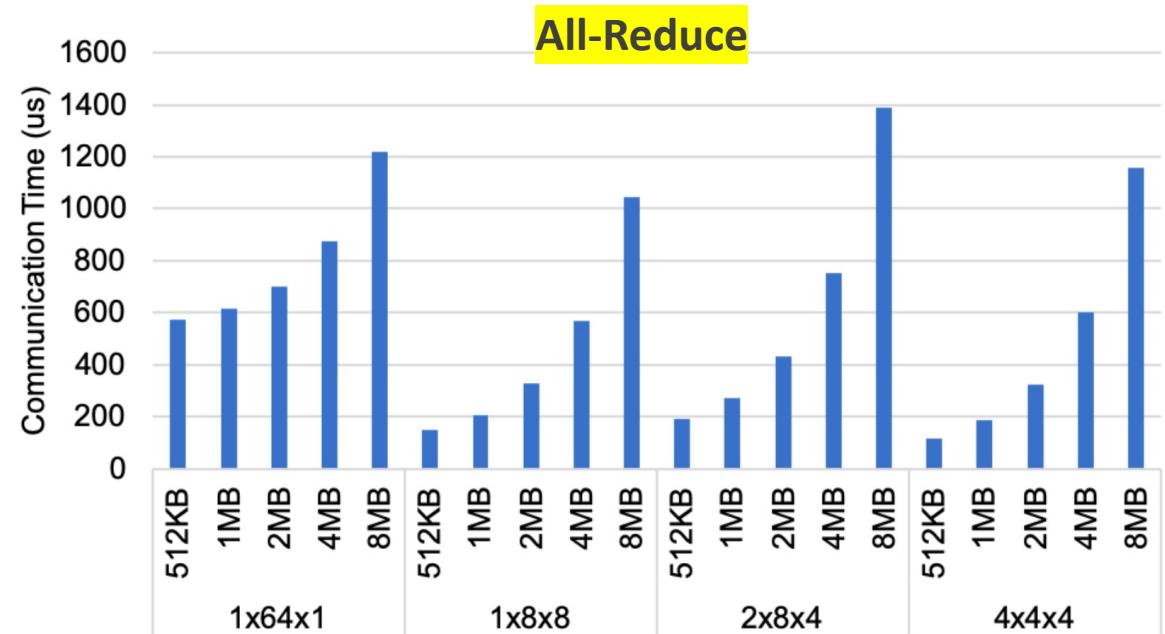
Target System



X * Y * Z dimension
X= cores within a package
Y= packages in horizontal dimension
Z= packages in vertical dimension

Impact of 1D/2D/3D Torus

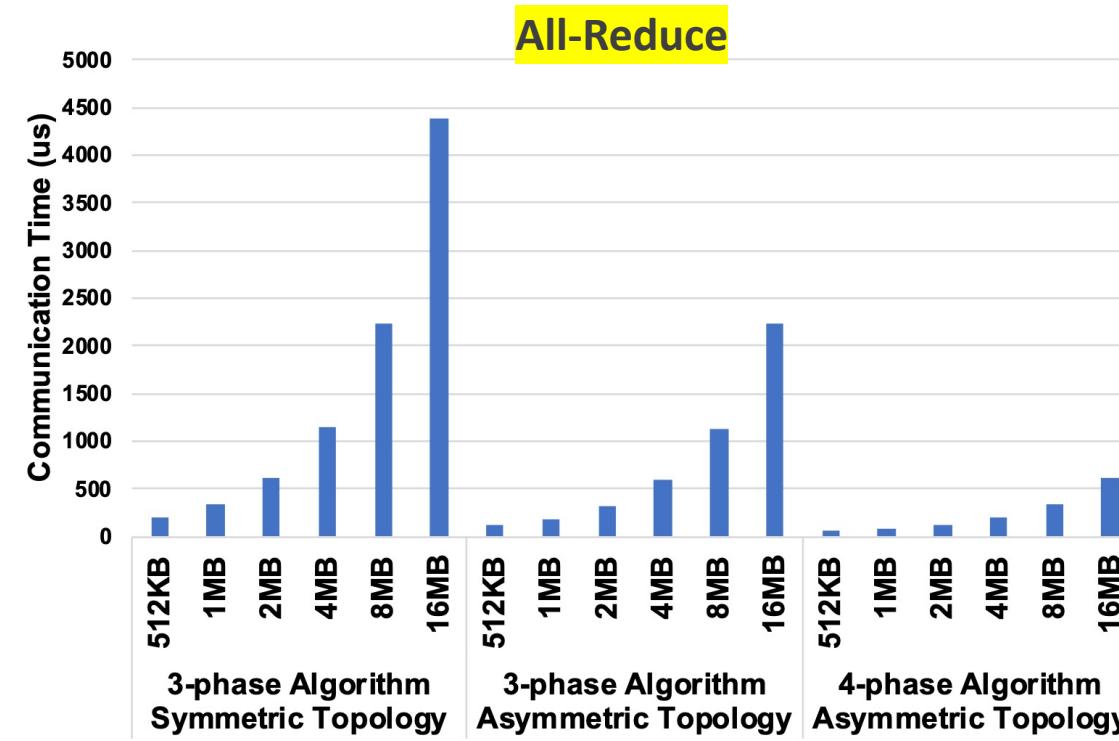
- Adding a dimension decreases the number of steps per collective.
 - For example, going from 1X64X1 to 1X8X8.
- Adding a dimension might increase amount of data each node sends out (depends on the algorithm).
 - For example, going from 1X8X8 to 2X8X4.
- Hence, choosing a topology is a tradeoff between the above 2 effects.



S. Rashidi et al., “ASTRA-SIM: Enabling SW/HW Co-Design Exploration for Distributed DL Training Platforms”, ISPASS 2020

Impact of Asymmetric Hierarchical Topology

- Having higher intra-package BW improves the performance.
- We can further improve performance by changing the algorithm to leverage this asymmetric BW.



S. Rashidi et al., “**ASTRA-SIM: Enabling SW/HW Co-Design Exploration for Distributed DL Training Platforms**”, ISPASS 2020

Distributed Training Stack

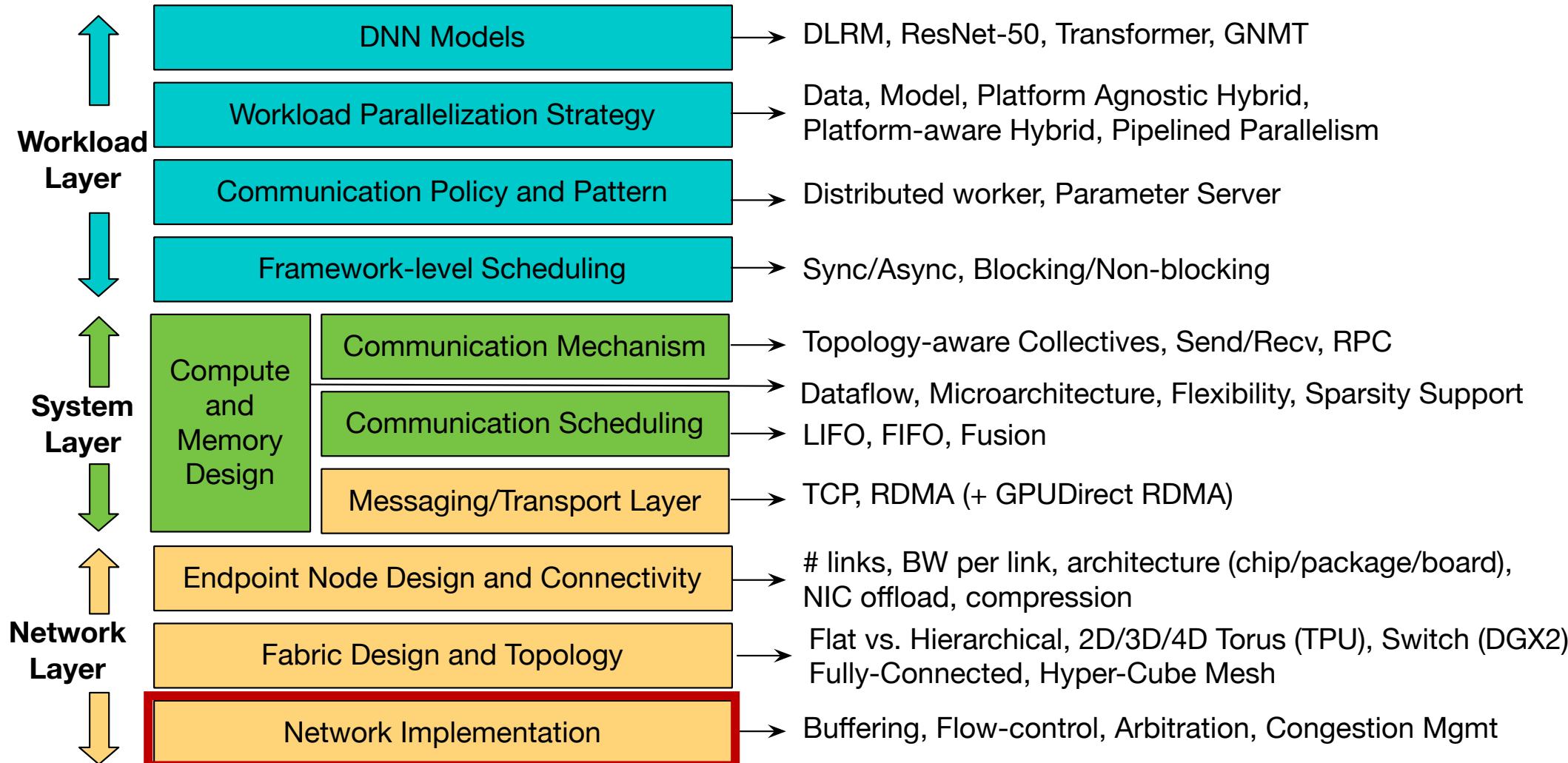
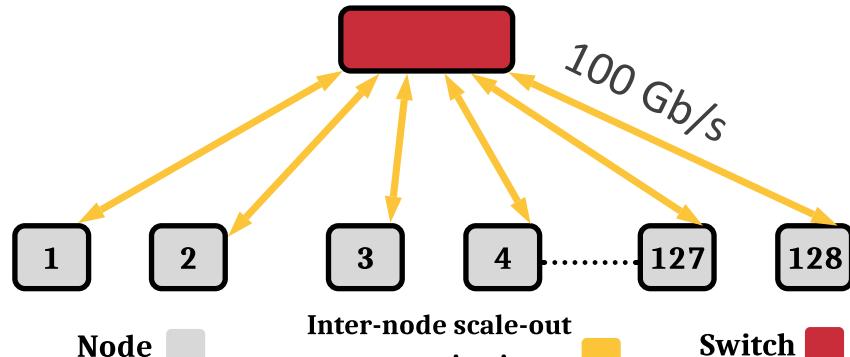
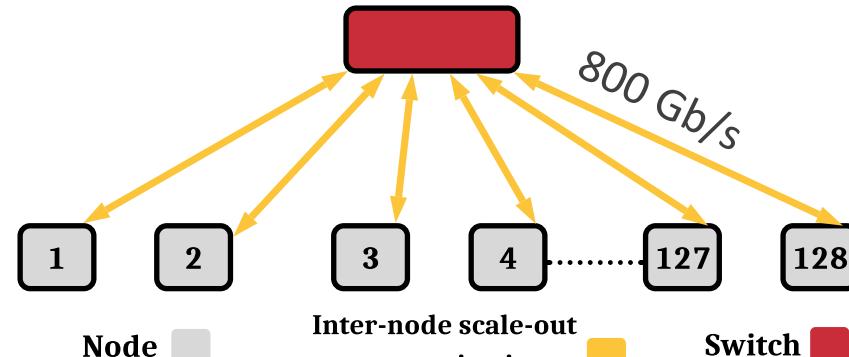


Figure Courtesy: Srinivas Sridharan (Facebook)

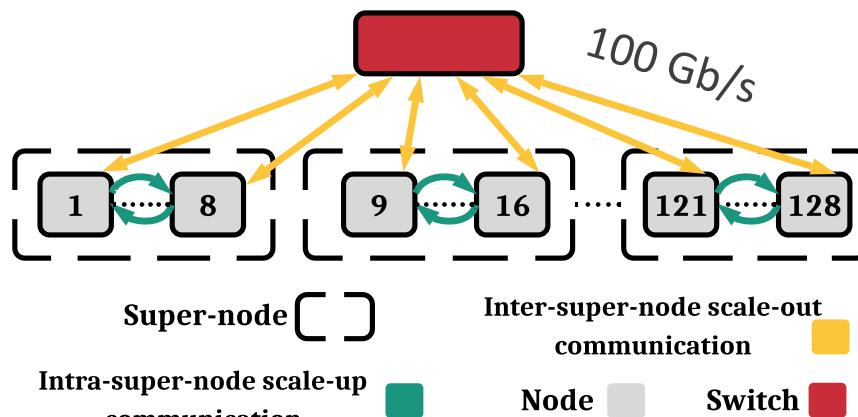
Target Systems



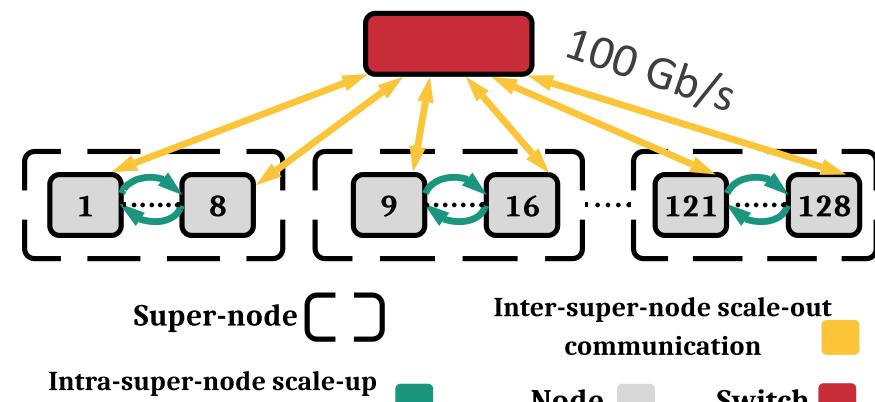
Flat100G
1-phase all-reduce



Flat800G
1-phase all-reduce



Hier
2-phase all-reduce

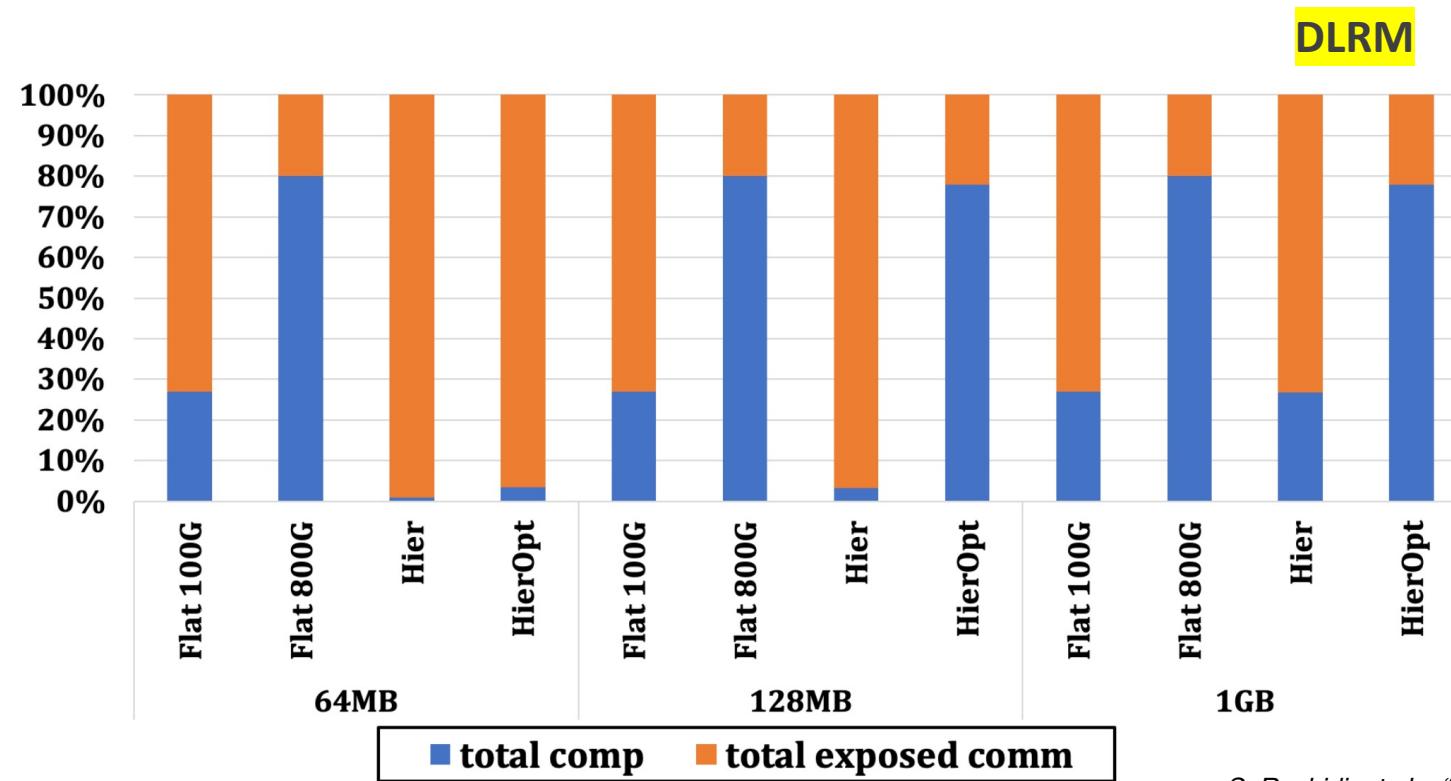


HierOpt
3-phase all-reduce

Effect of Size of Switch Buffer

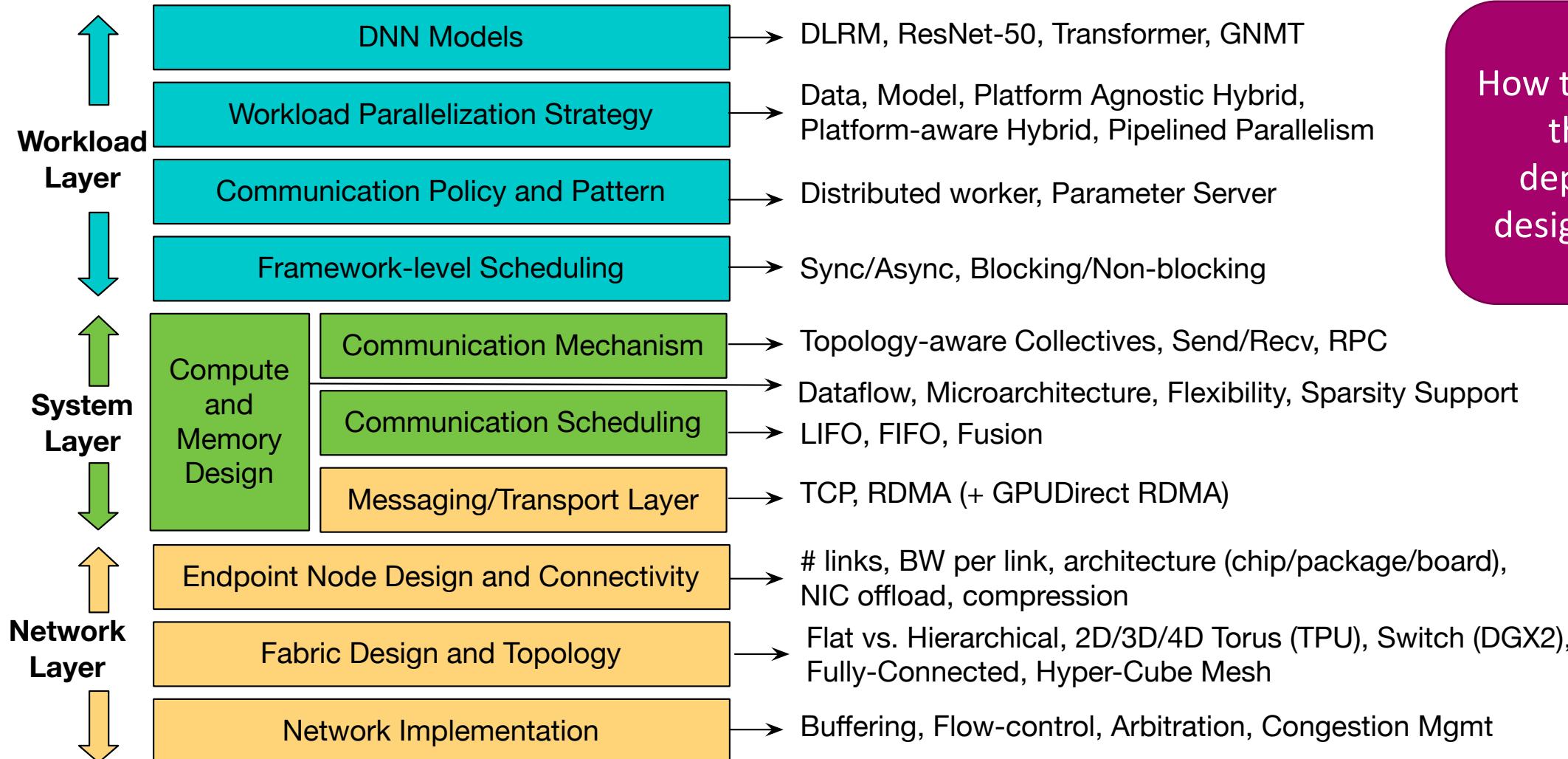
Observations:

- Flat vs. Hierarch different Sensitivity to global switch size



S. Rashidi, et al., “Scalable Distributed Training of Recommendation Models: An ASTRA-SIM + NS3 case-study with TCP/IP transport”, Hot Interconnects 2020

Distributed Training Stack



How to navigate
this co-
dependent
design-space?

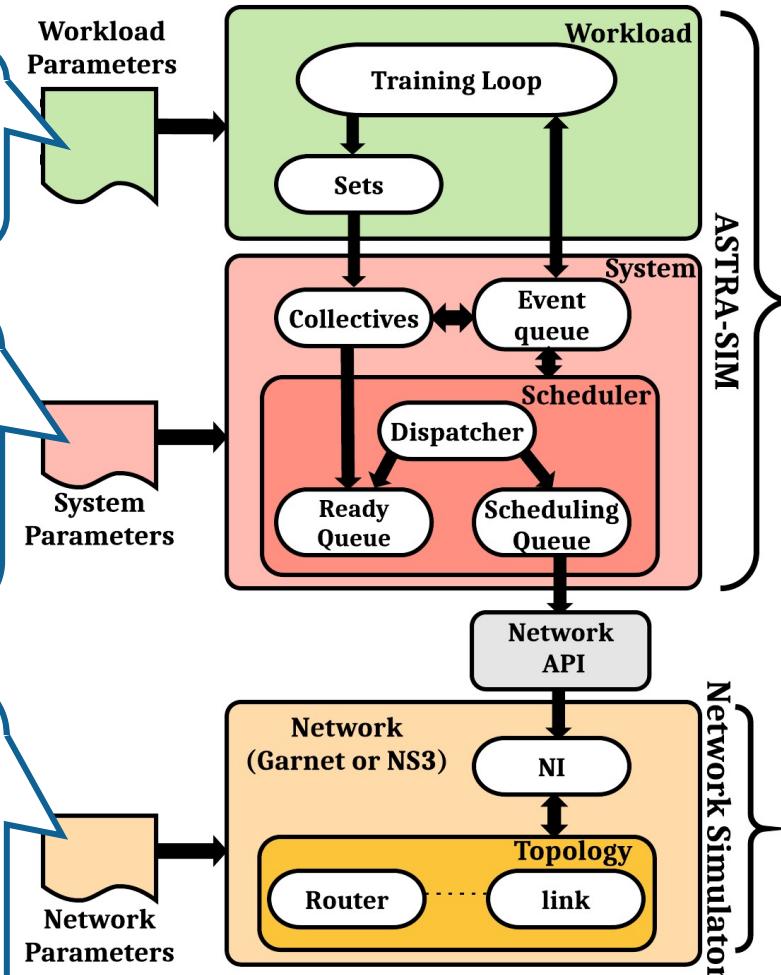
Figure Courtesy: Srinivas Sridharan (Facebook)

Introducing ASTRA-sim

- ✓ Supports Data-Parallel, Model-Parallel, Hybrid-Parallel training loops
- ✓ Extensible to more training loops

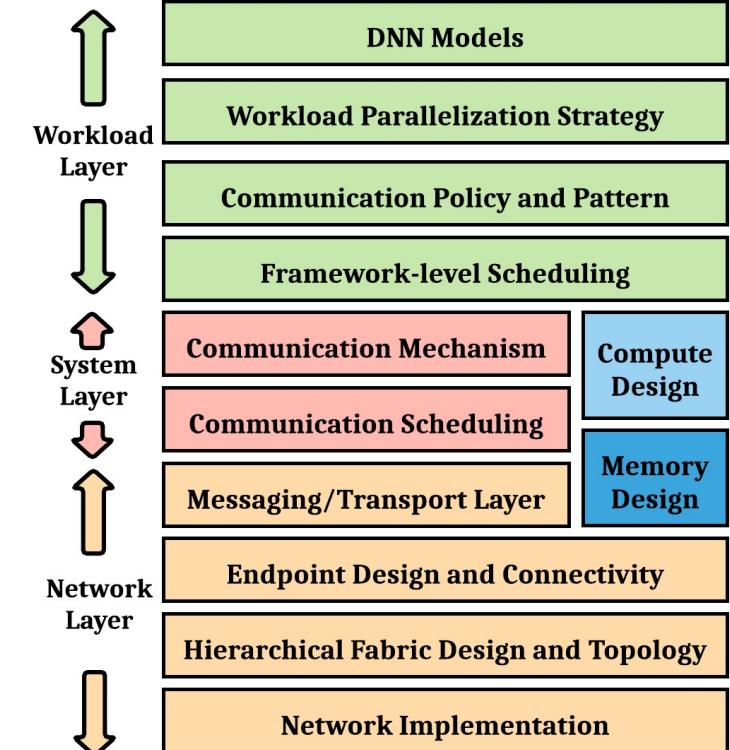
- ✓ Ring based, Tree-based, AlltoAll based, and multi-phase collectives
- ✓ Variety of scheduling policies
- ✓ Compute times fed via offline system measurements or compute simulator

- ✓ Various topologies, flow-control, link bandwidth, congestion control
- ✓ Plug-and-play options
 - ✓ Analytical (roofline) - released
 - ✓ Garnet (credit-based) - released
 - ✓ NS3 (TCP, RDMA) – in progress



<http://github.com/astra-sim/astra-sim>

DL Training Co-Design Stack



S. Rashidi et al., “**ASTRA-SIM: Enabling SW/HW Co-Design Exploration for Distributed DL Training Platforms**”, ISPASS 2020

S. Rashidi, et al., “**Scalable Distributed Training of Recommendation Models: An ASTRA-SIM + NS3 case-study with TCP/IP transport**”, Hot Interconnects 2020

What Does ASTRA-sim Report?

ASTRA-sim Reports:

1. End-to-end training time.
2. Total communication time for each communication operation.
3. The amount of **exposed communication** for each communication operation.
4. Total Exposed communication and total computation.
5. More detailed stats such as average message latency per each hierarchical collective phase.

Network Backend Specific Reports (Depends on the network backend type):

1. Network BW utilization
2. Communication protocol stats, such as packet drops, # of retransmissions, etc.
3. Network switch buffer usage
4. ...

Summary and Takeaways

- Large Model distributed training is an ongoing open-research area
- Many emerging supercomputing systems being designed specifically for this problem!
 - Cerebras CS2
 - Tesla Dojo
 - NVIDIA DGX + Mellanox SHARP switches
 - Intel Habana
 - IBM Blueconnect
 - ...
- Co-design of algorithm and system offers high opportunities for speedup and efficiency

Agenda

Time (CET)	Time (ET)	Topic	Presenter
15:00 – 16:00	9:00 – 10:00	Introduction to Distributed Deep Learning Training Platforms	Tushar Krishna
16:00 – 17:00	10:00 – 11:00	ASTRA-sim	Saeed Rashidi
17:00 – 17:10	11:00 – 11:10	Break	
17:10 – 17:50	11:10 – 11:50	Demo and Exercises	William Won and Taekyung Heo
17:50 – 18:00	11:50 – 12:00	Extensions and Future Development	Tushar Krishna and Saeed Rashidi

Tutorial Website

includes agenda, slides, ASTRA-sim installation instructions (via source + docker image)

<https://astra-sim.github.io/tutorials/asipos-2022>

Attention: Tutorial is being recorded