

Systems for Scalable ML - DNN Training

Yiying Zhang

Outline

- DNN basics
- Distributed DNN training
 - Data parallelism
 - Model parallelism (including PipeDream and Alpa)

Lecture 13

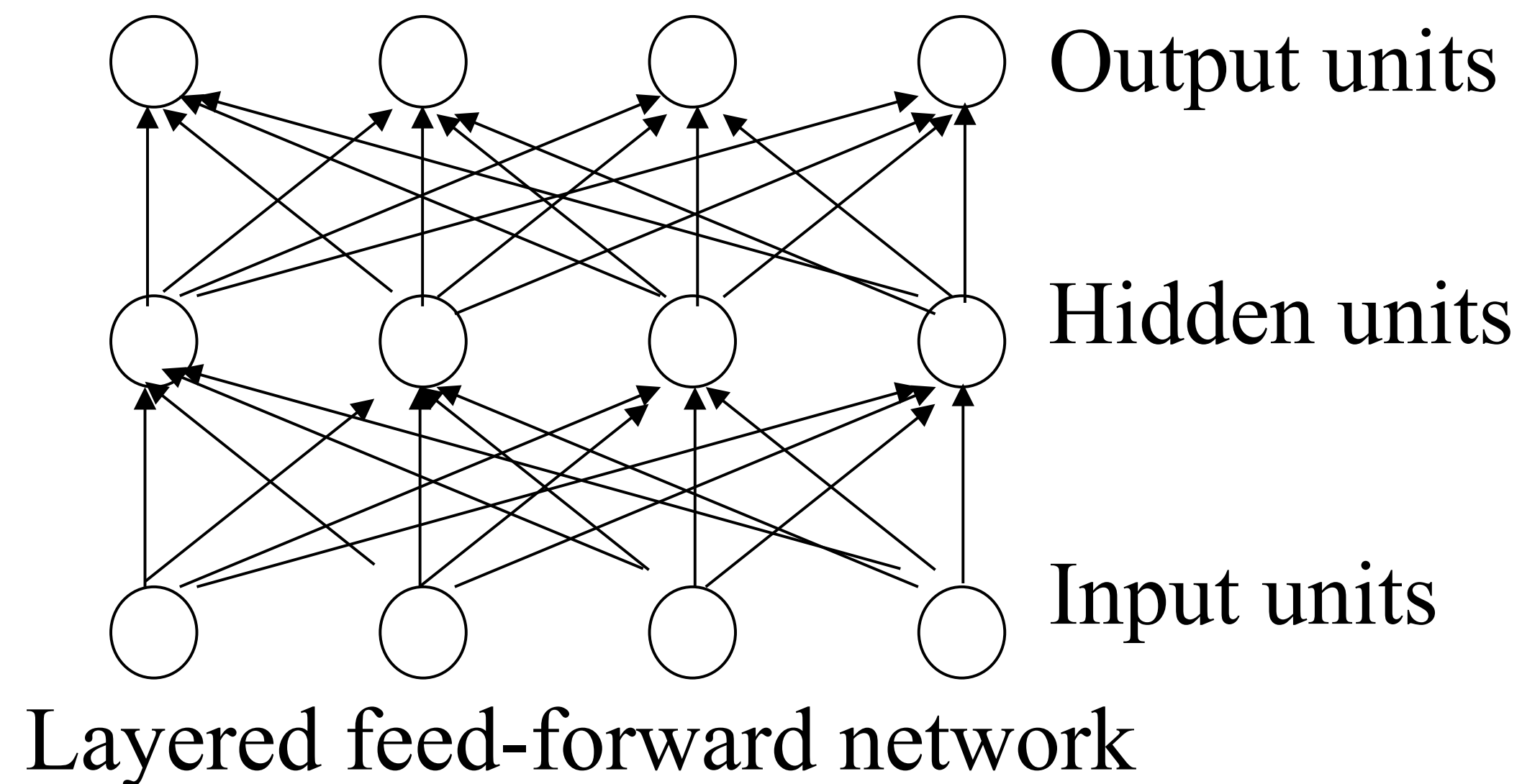
Distributed Training

Song Han

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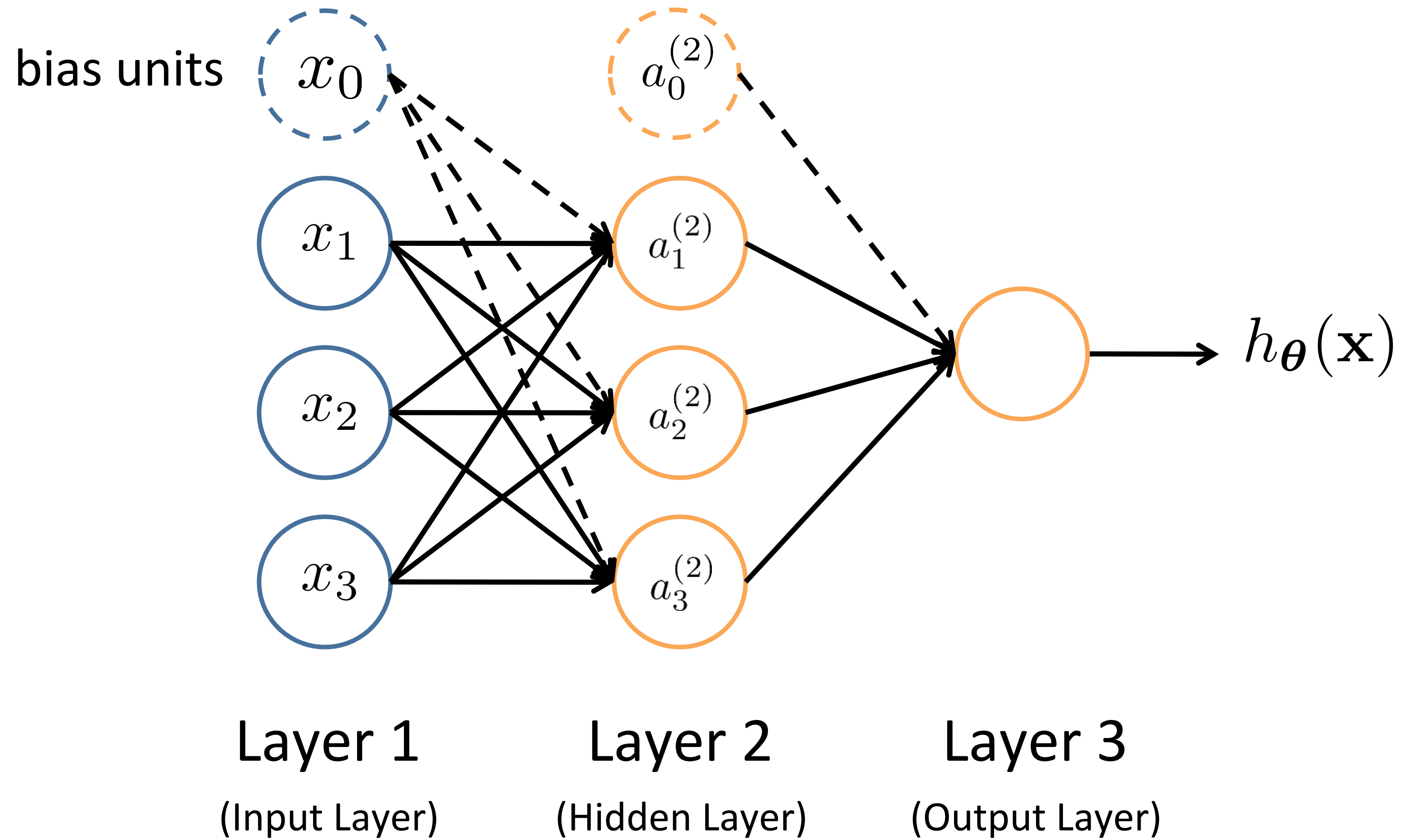


Neural networks



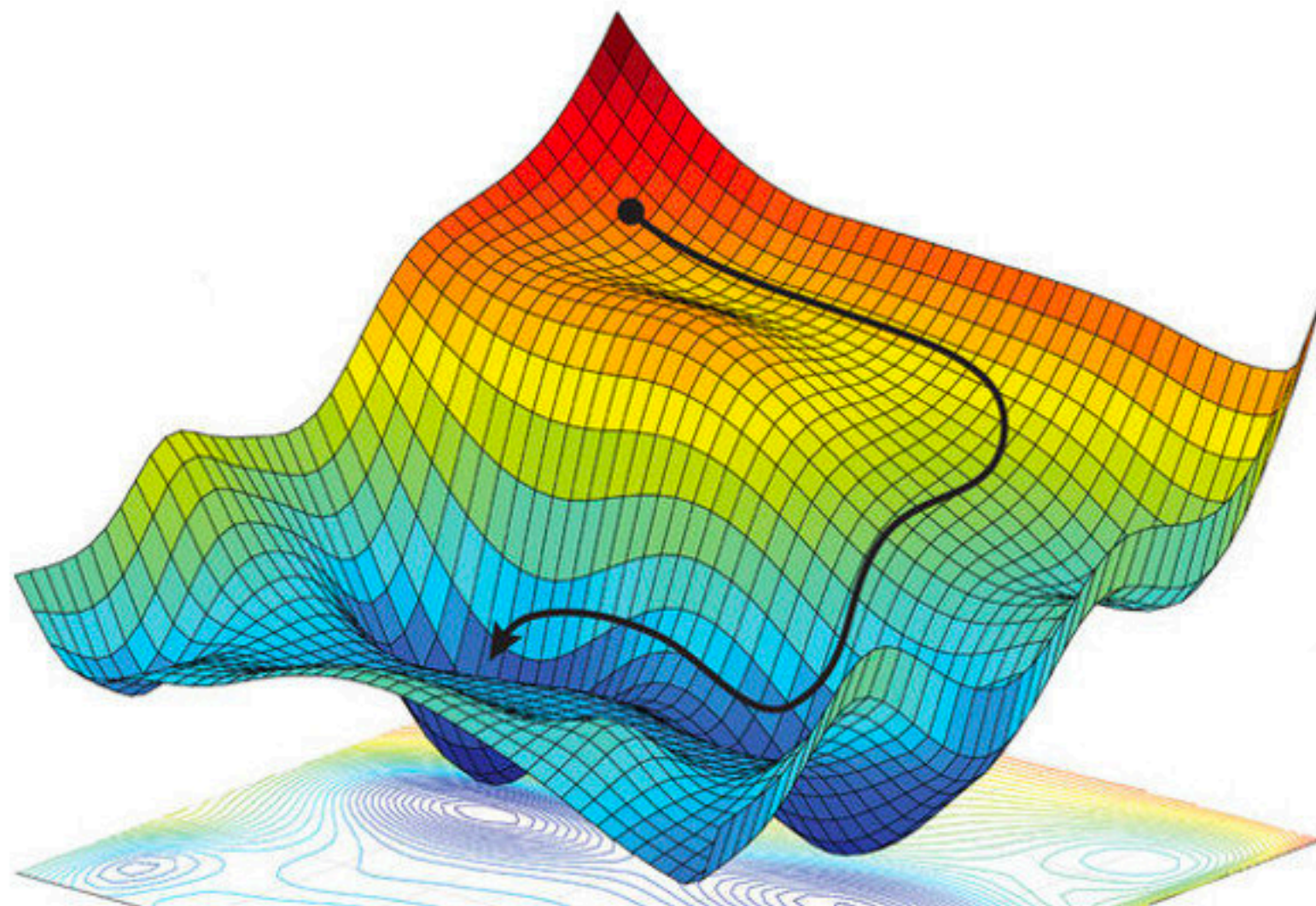
- Neural networks are made up of **nodes** or **units**, connected by **links**
- Each link has an associated **weight** and **activation level**
- Each node has an **input function** (typically summing over weighted inputs), an **activation function**, and an **output**

Neural Network

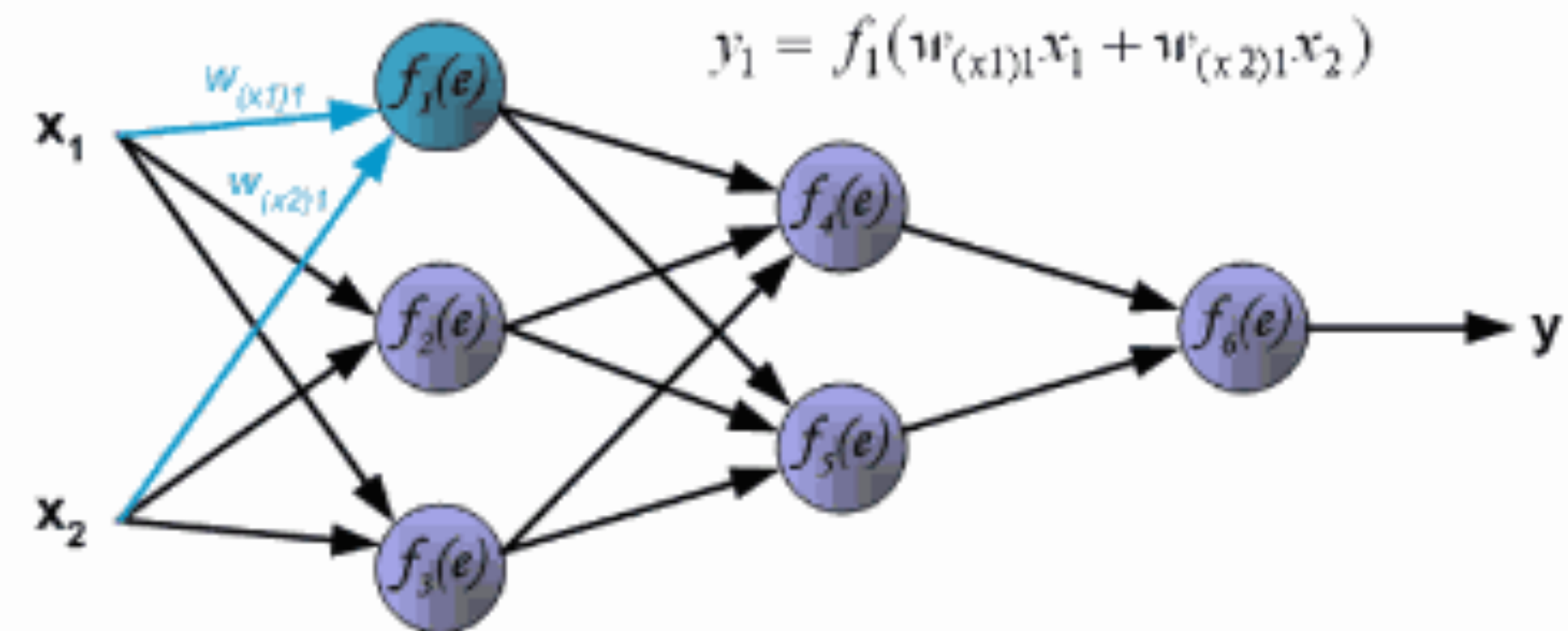


Neural Network Training

- Feedforward and back propagation gradient descend

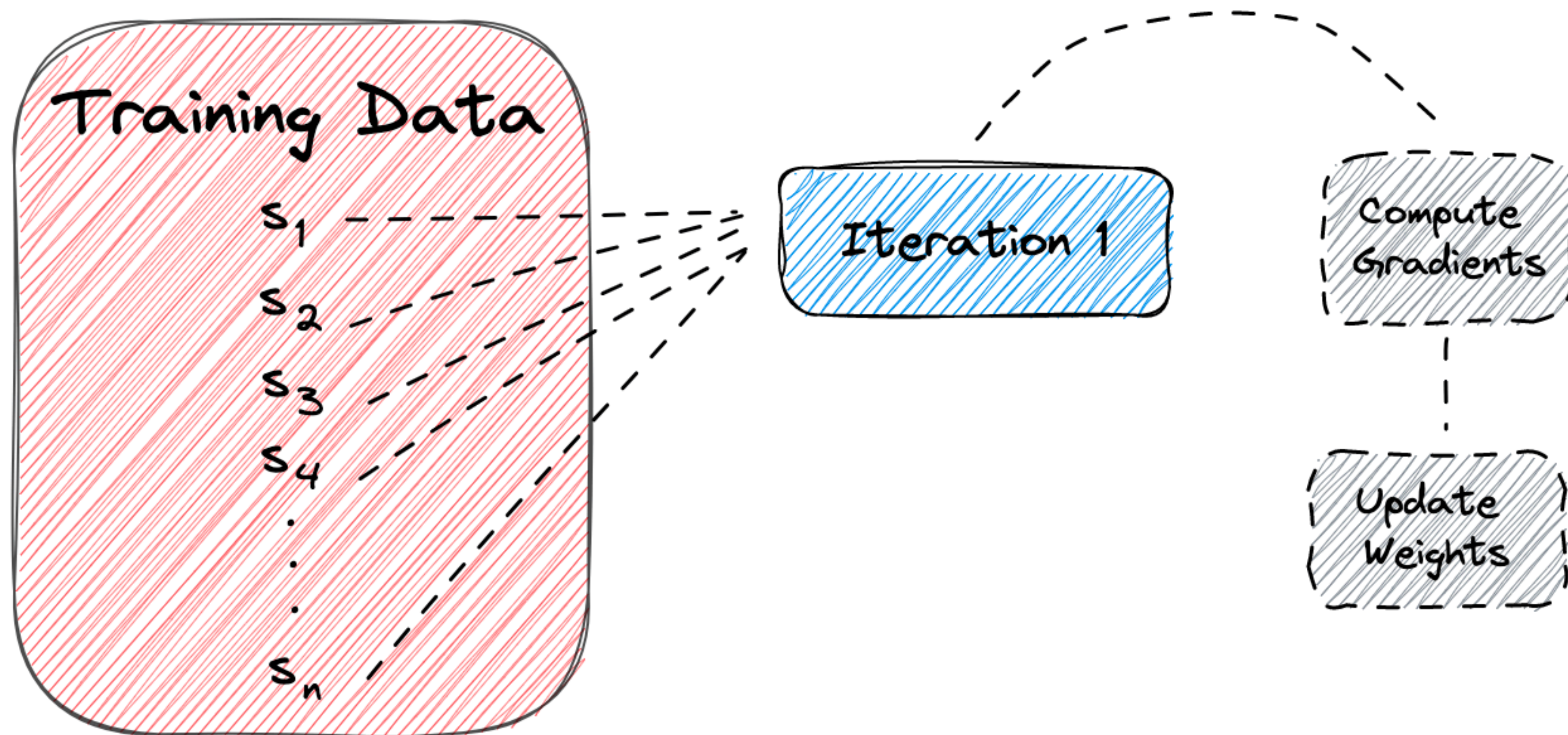


source: <https://arxiv.org/abs/1805.04829>



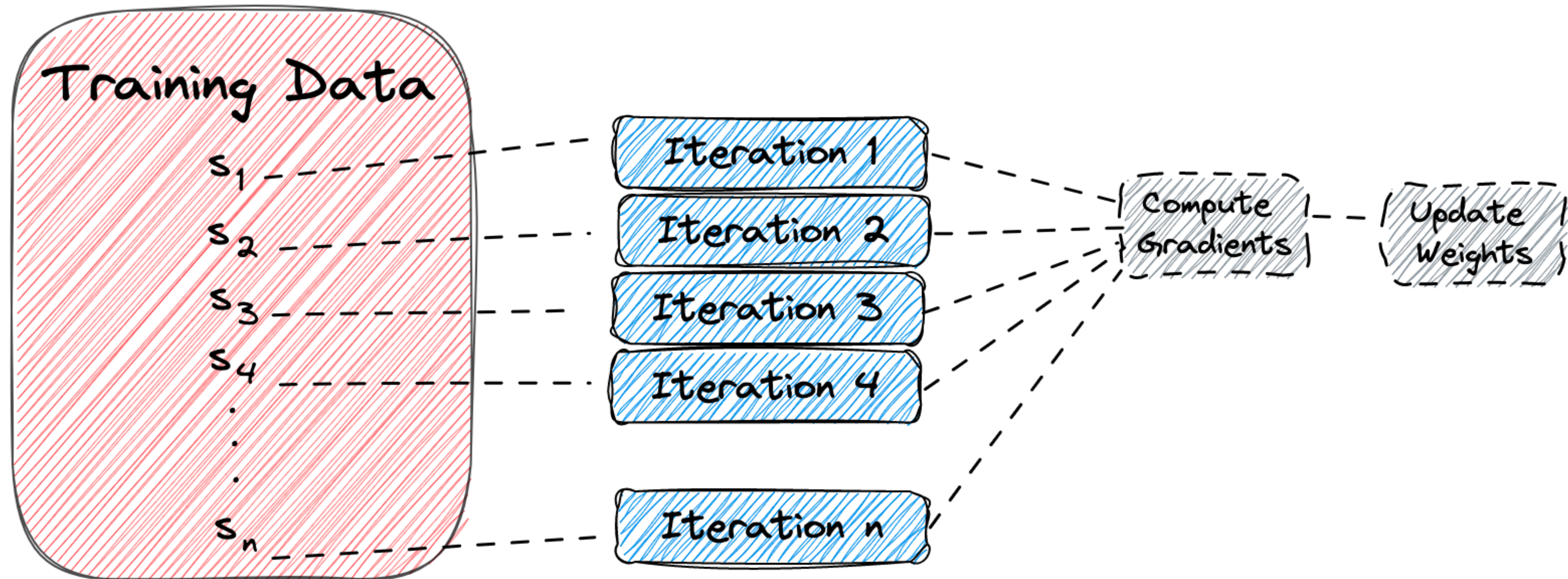
source: <https://www.programmersought.com/article/45312377380/>

Batch Gradient Descent



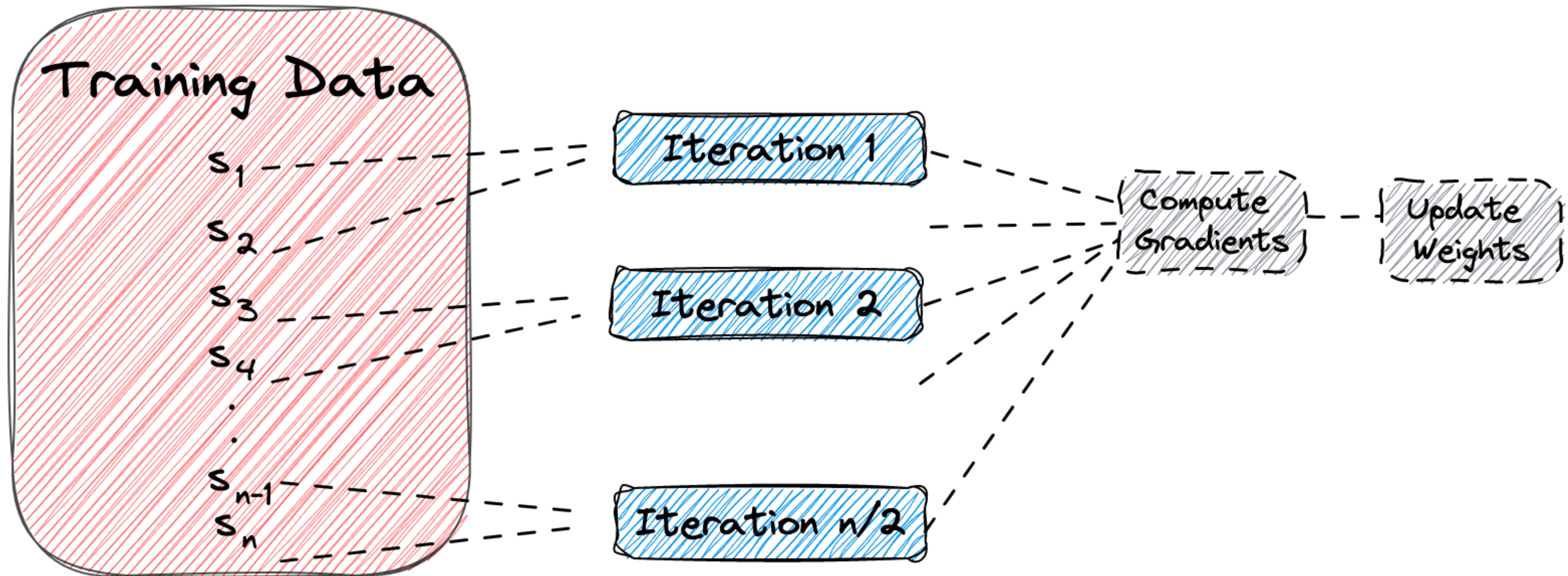
source: <https://www.baeldung.com/cs/epoch-vs-batch-vs-mini-batch>

Stochastic Gradient Descent



source: <https://www.baeldung.com/cs/epoch-vs-batch-vs-mini-batch>

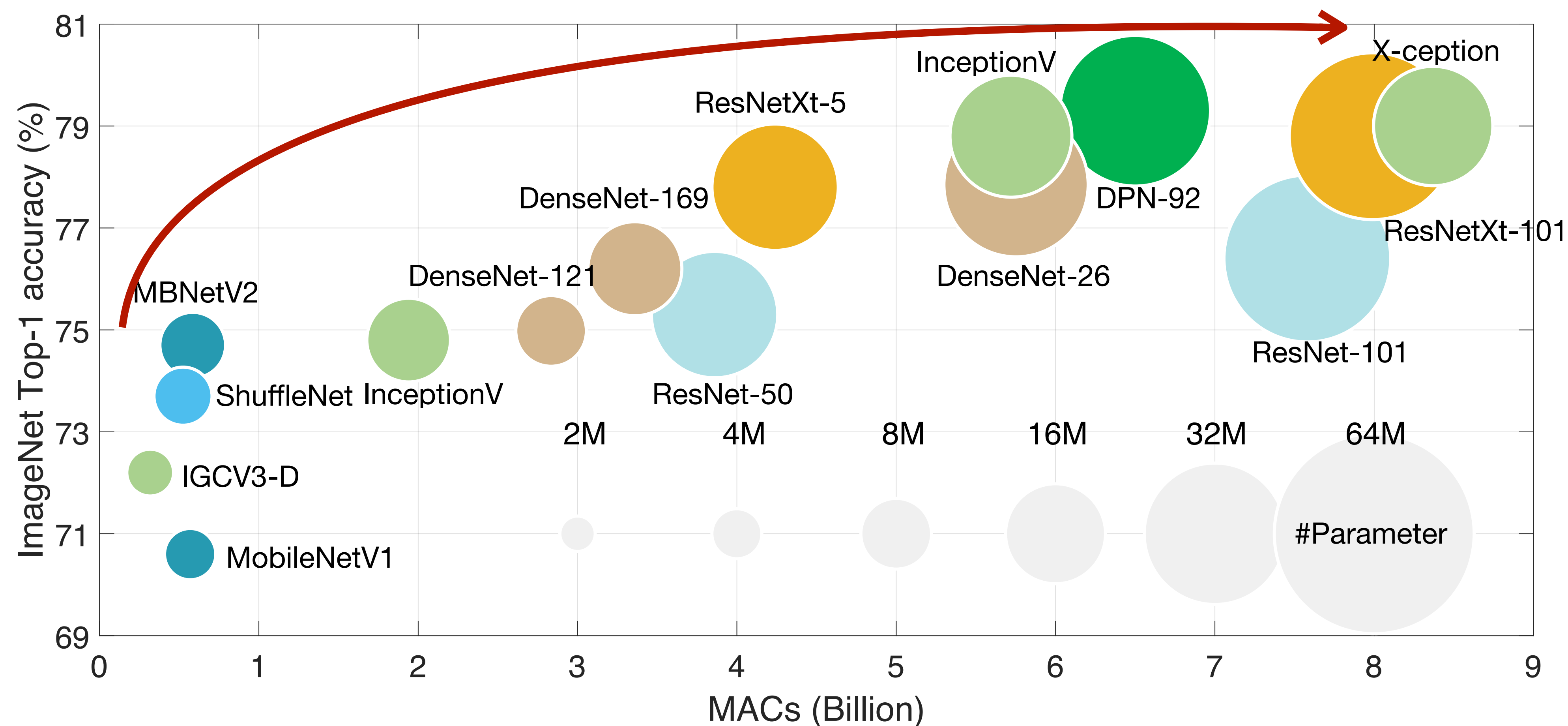
Minibatch-Based SGD



source: <https://www.baeldung.com/cs/epoch-vs-batch-vs-mini-batch>

Models are getting larger and larger

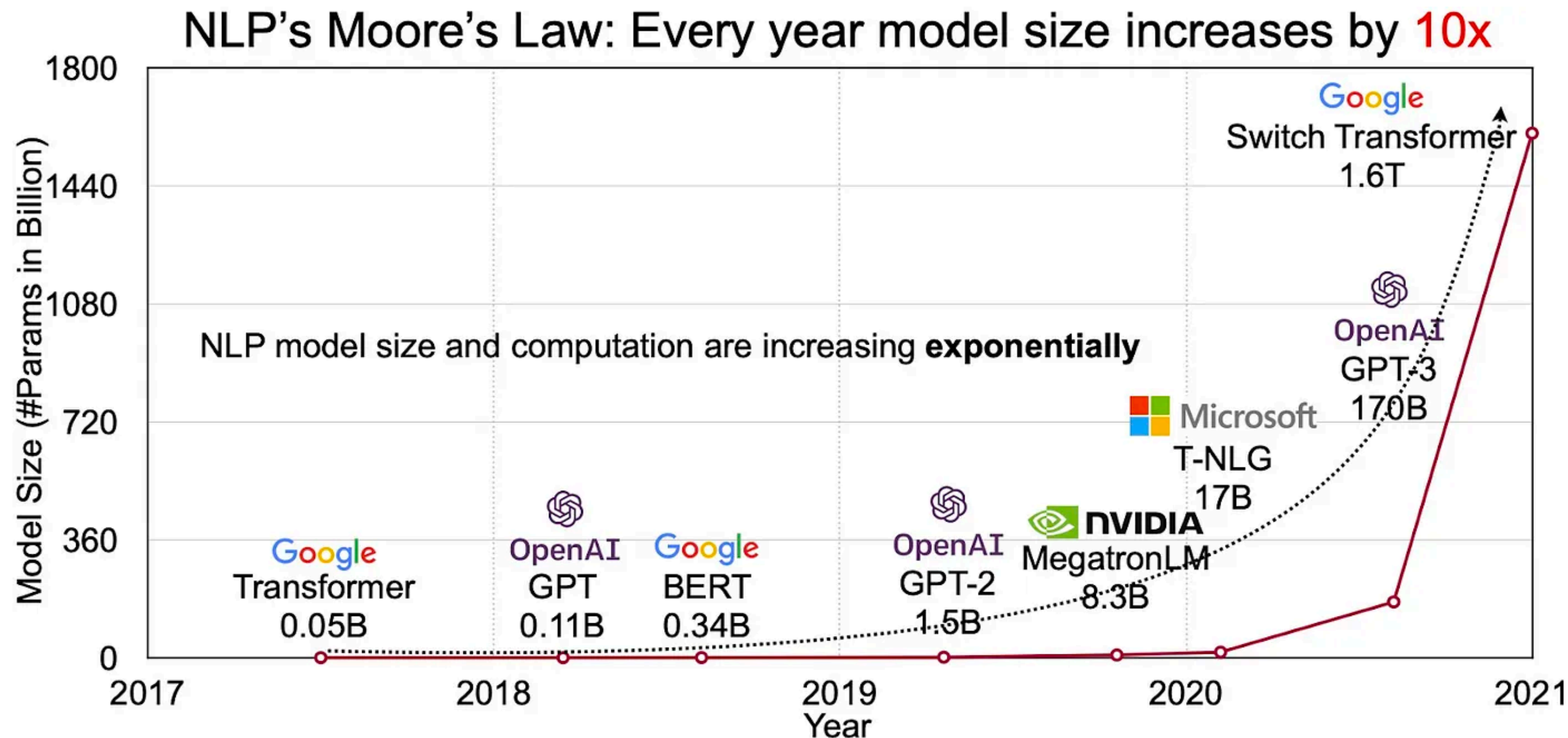
Better model always comes with higher computational cost (vision)



Figures from Once-for-all project page.

Models are getting larger and larger

Better model always comes with higher computational cost (NLP)



source: <https://indiaai.gov.in/article/the-future-of-large-language-models-llms-strategy-opportunities-and-challenges>

Models are getting larger and larger

Large Models Take Longer Time to Train

Models	#Params (M)	Training Time (GPU Hours)
ResNet-50	26	31
ResNet-101	45	44
BERT-Base	108	84
Turing-NLG 17B	17,000	TBA
GPT-3 175B	175,000	3,100,000

Measured on Nvidia A100

If without distributed training, a single GPU would take **335 years** to finish GPT-3!

Distributed Training is Necessary

- Developers / Researchers' time **are more valuable** than hardware .
- If a training takes **10 GPU days**
 - Parallelize with distributed training
 - 1024 GPUs can finish in 14 minutes (ideally)!
- The develop and research cycle will be greatly boosted

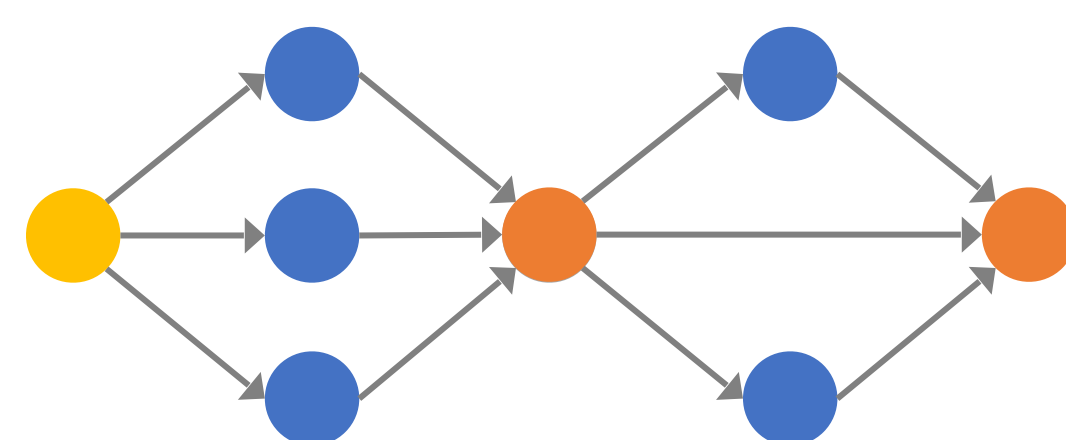
Let's see a use case of distributed training!

Parallelism in Distributed Training

- **Data Parallelism**
- Model Parallelism
- Compare the Advantages and Disadvantages of Two Parallelism

Introduction to Distributed Training

Data Parallelism

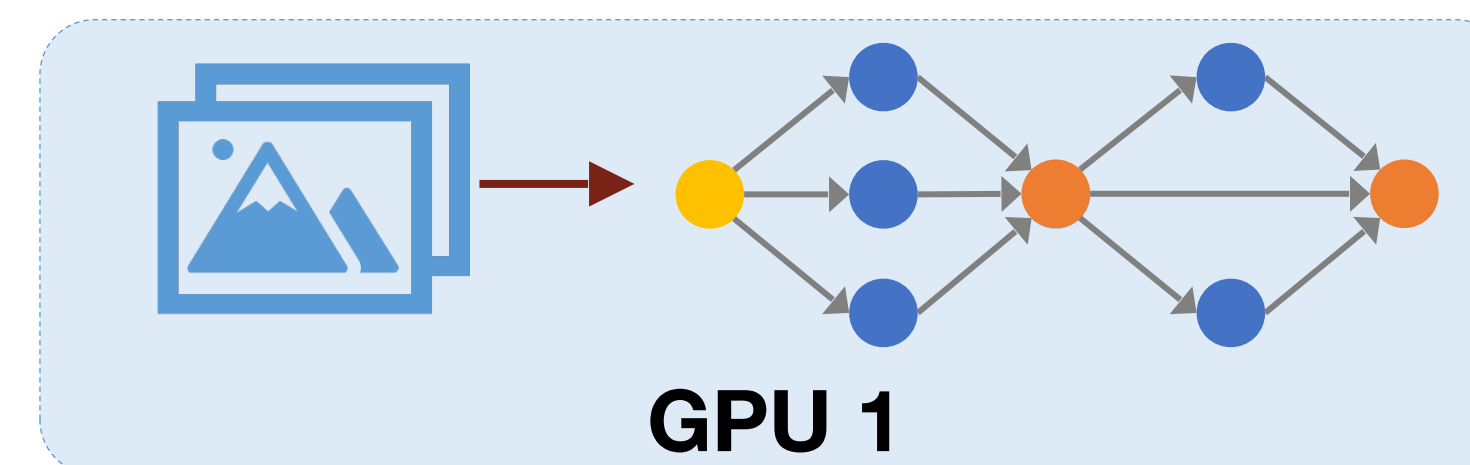


ML Model

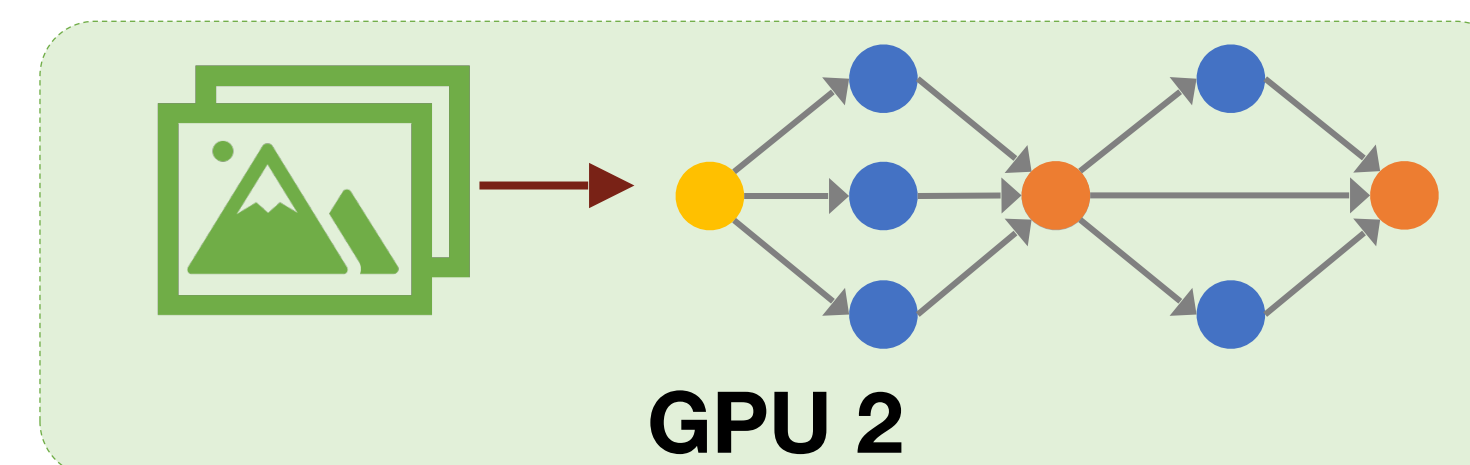


Training Dataset

Data Parallelism

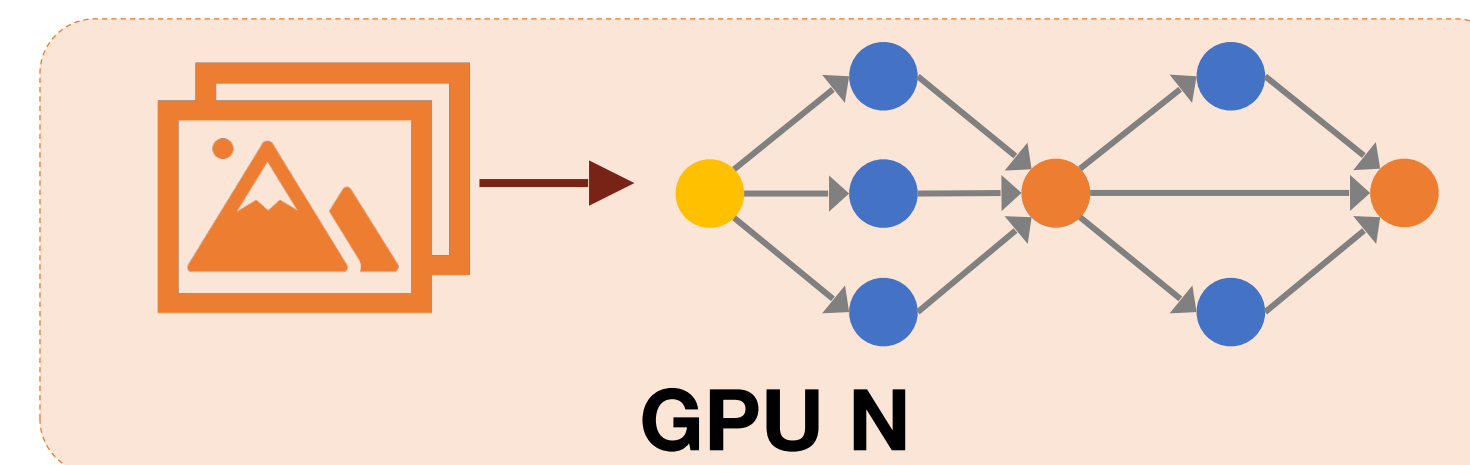


GPU 1



GPU 2

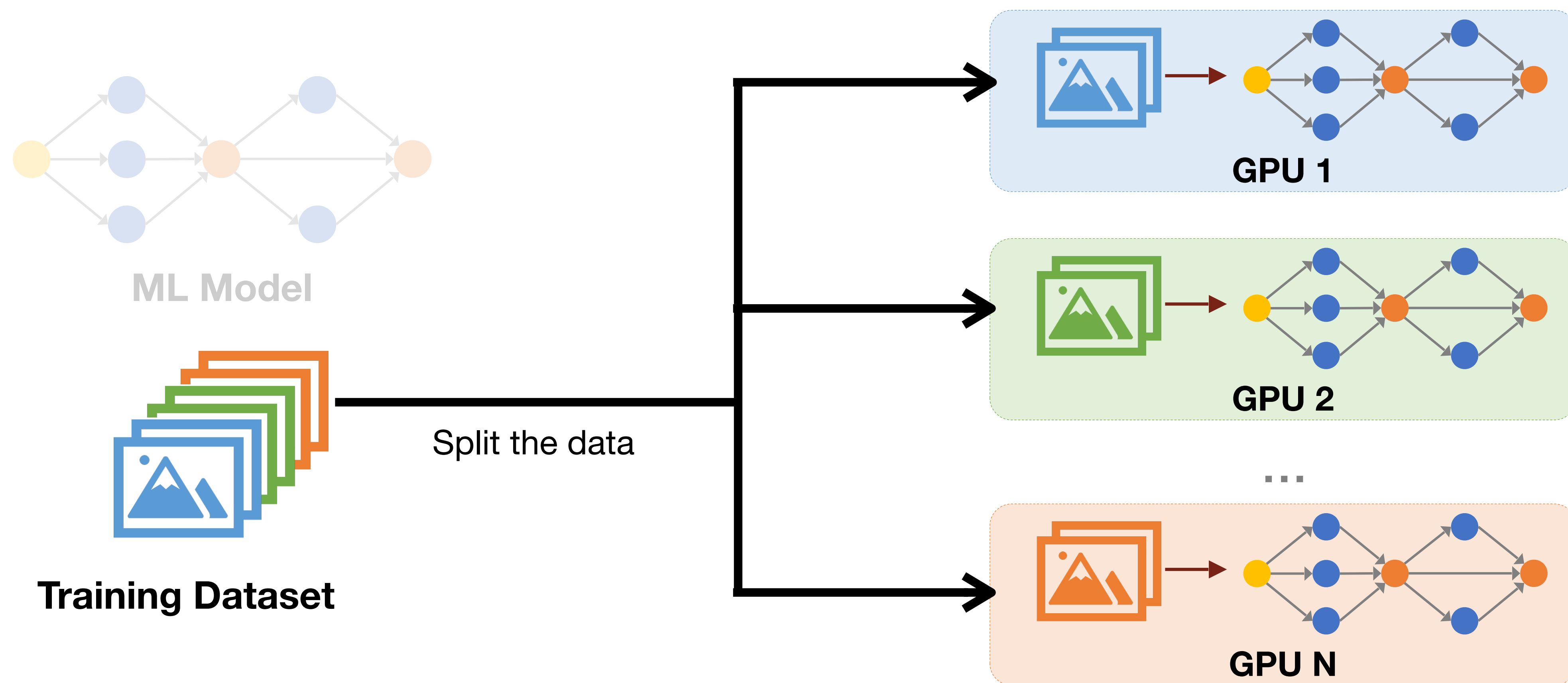
...



GPU N

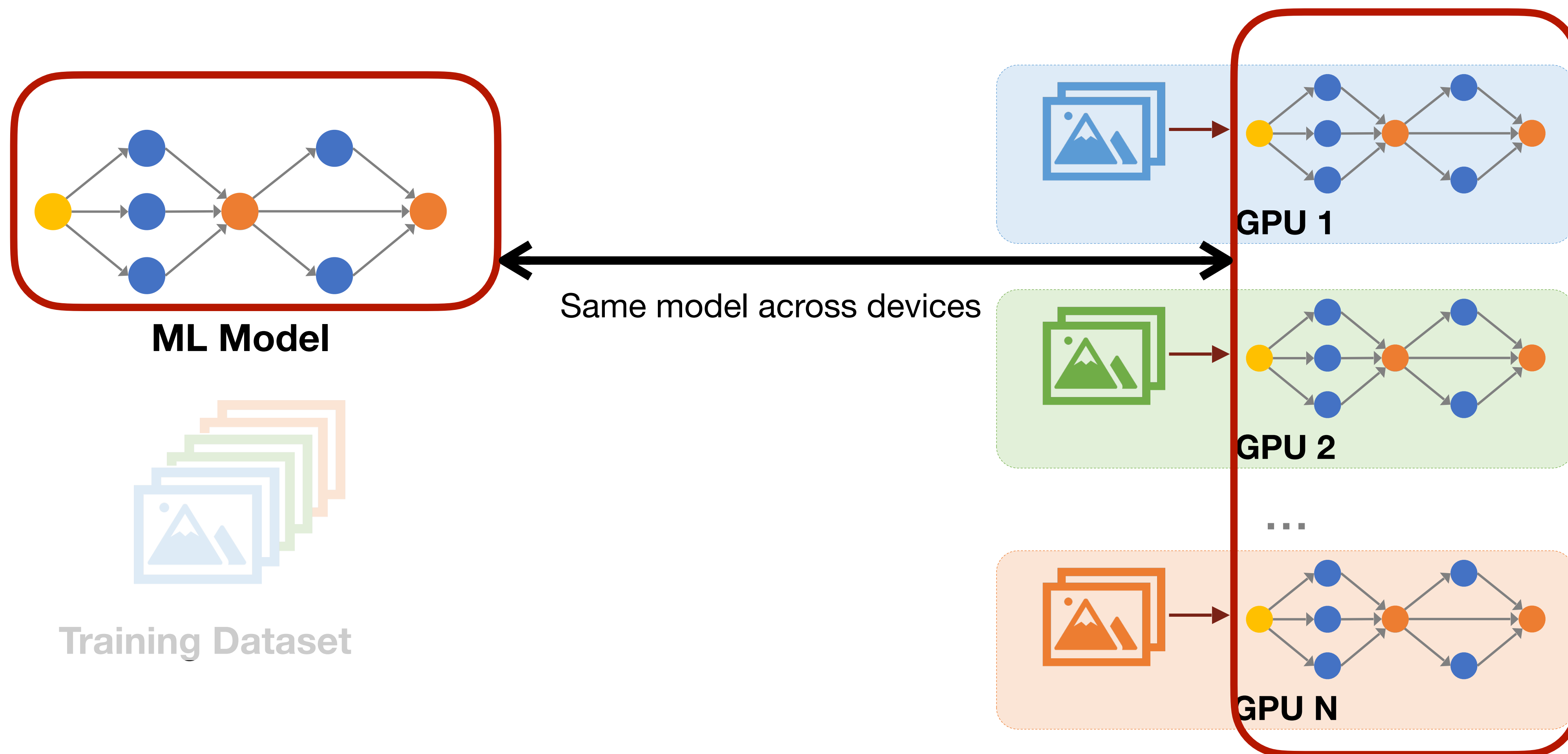
Introduction to Distributed Training

Data Parallelism



Introduction to Distributed Training

Data Parallelism

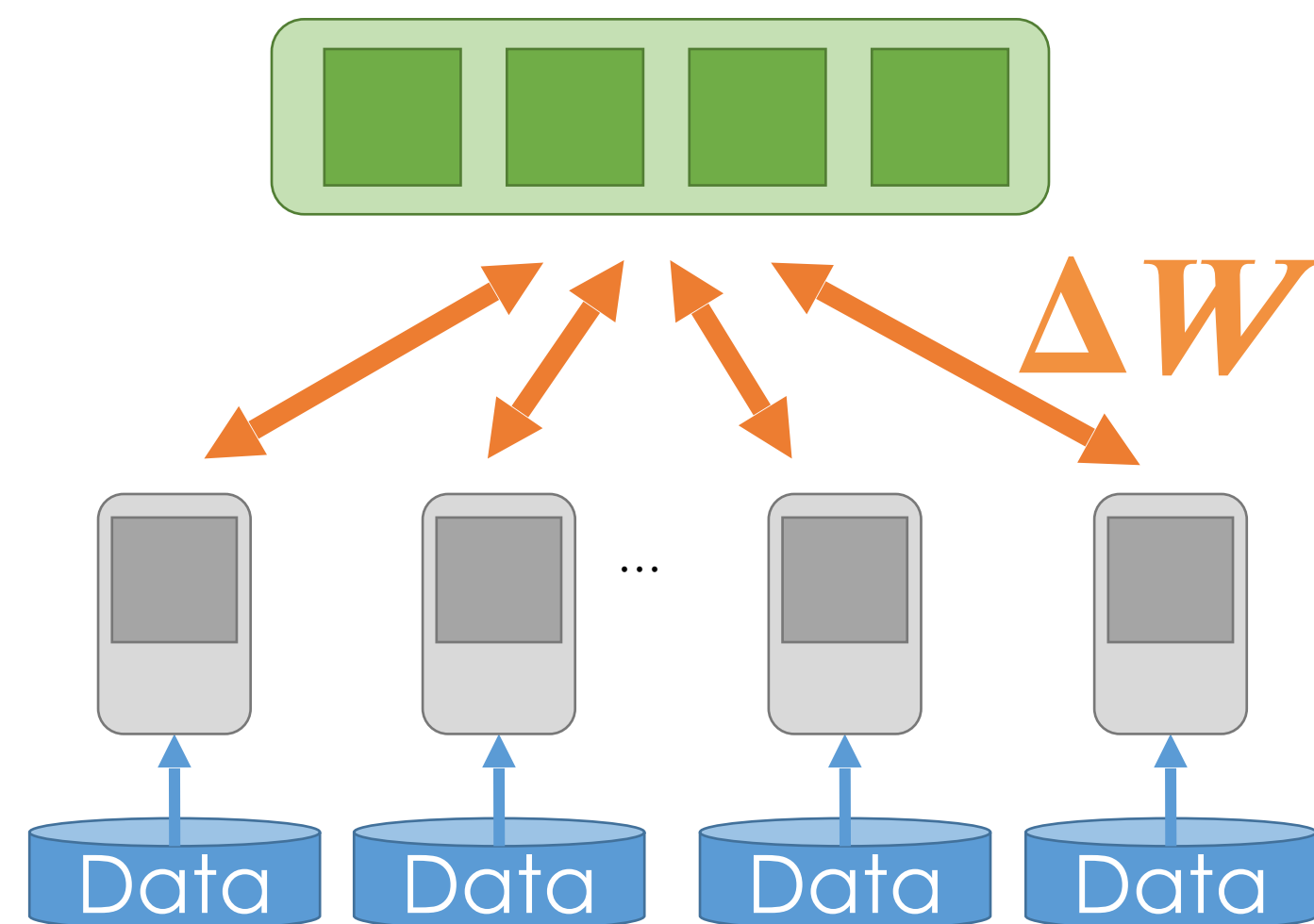


Dive into Data Parallelism

Scaling Distributed Machine Learning with the Parameter Server

Parameter Server

The central controller of the whole training process



Worker nodes

The hardware accelerators and dataset storage.

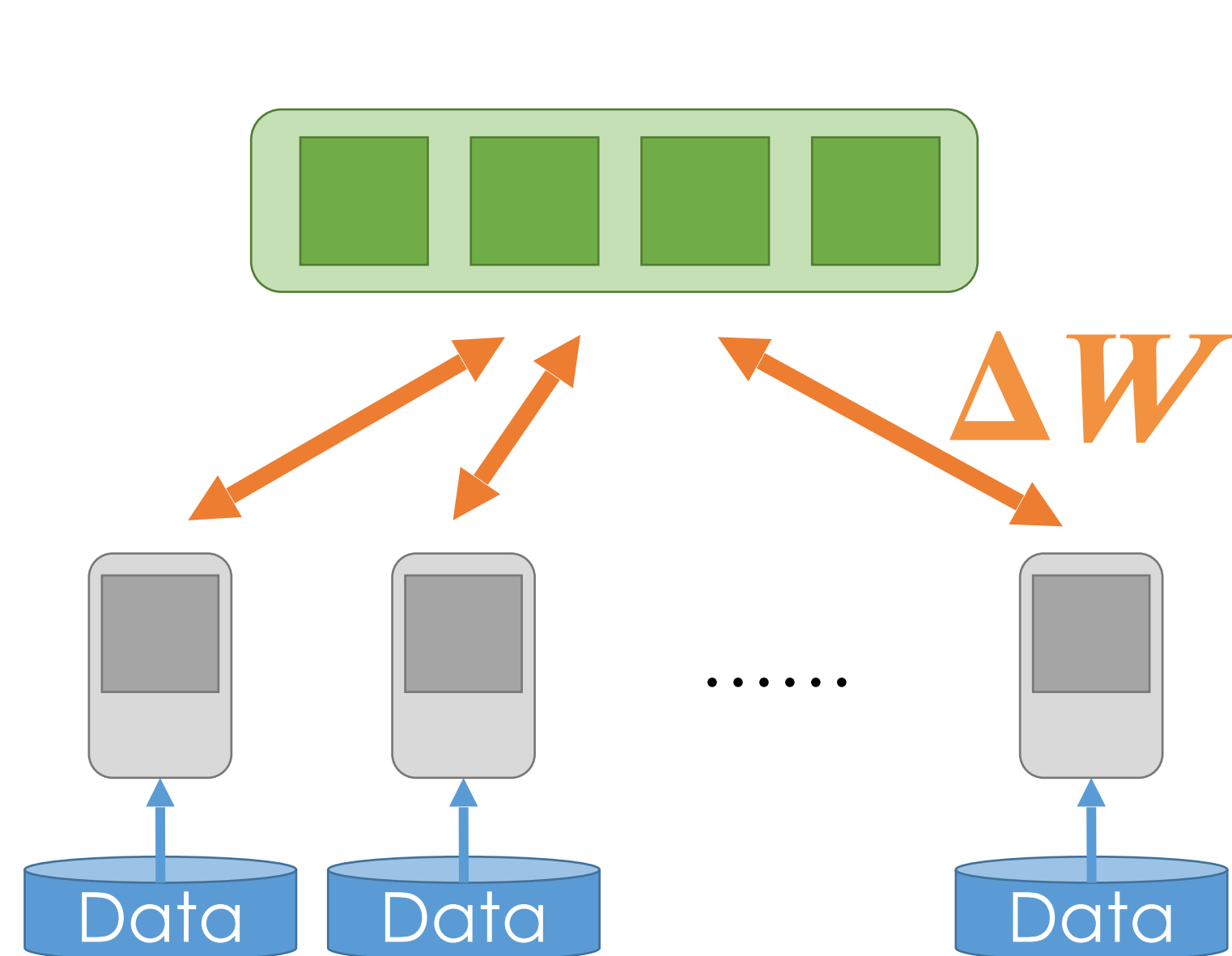
Two different roles in framework:

- **Parameter Server**: receive gradients from workers and send back the aggregated results
- **Workers**: compute gradients using splitted dataset and send to parameter server

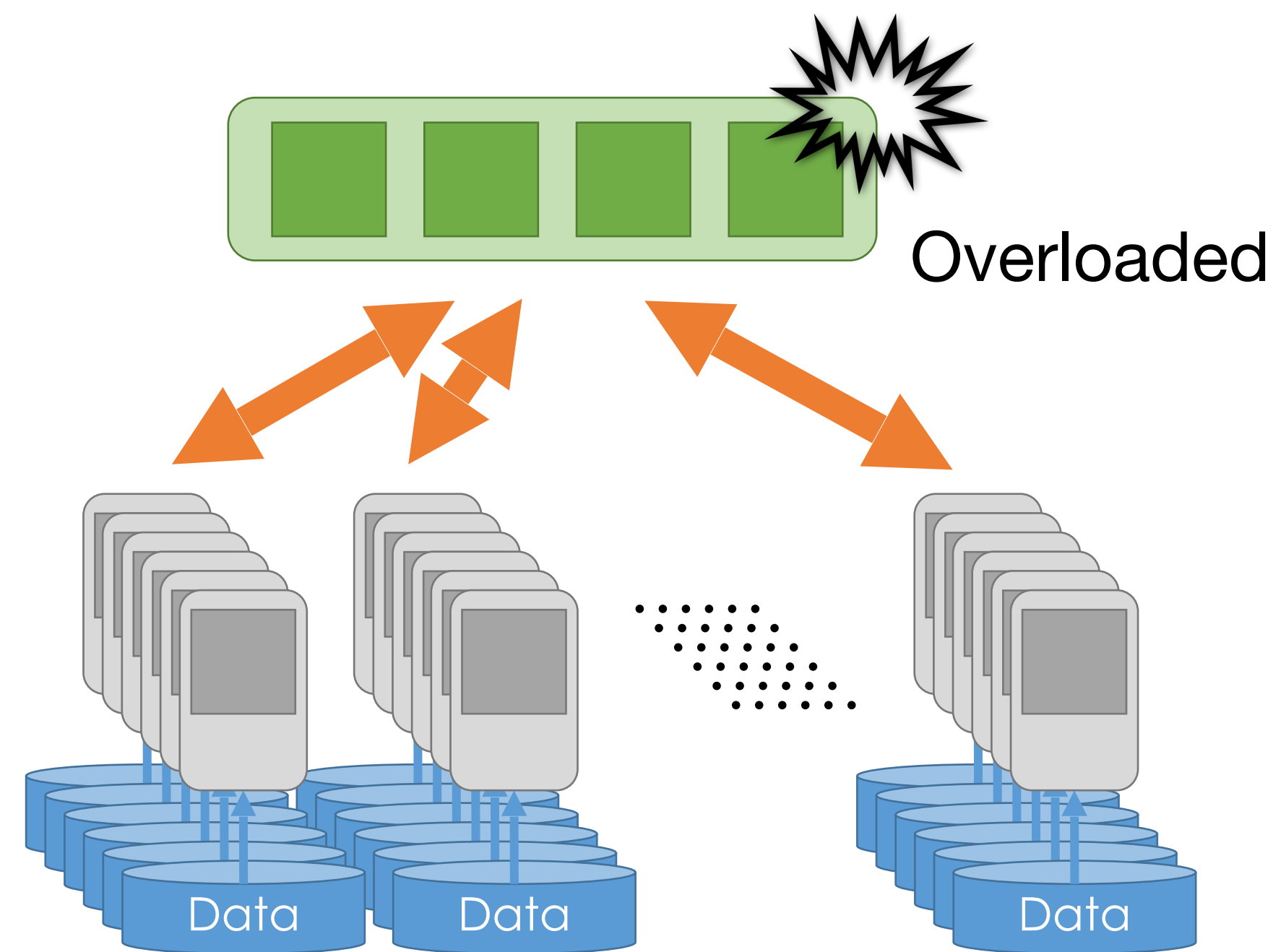
Scaling Distributed Machine Learning with the Parameter Server. Mu Li et al. 2014

Figure credits from: Deep Gradient Compression. Lin et al. 2018

Problems with Parameter Server



When number of workers is small 😊



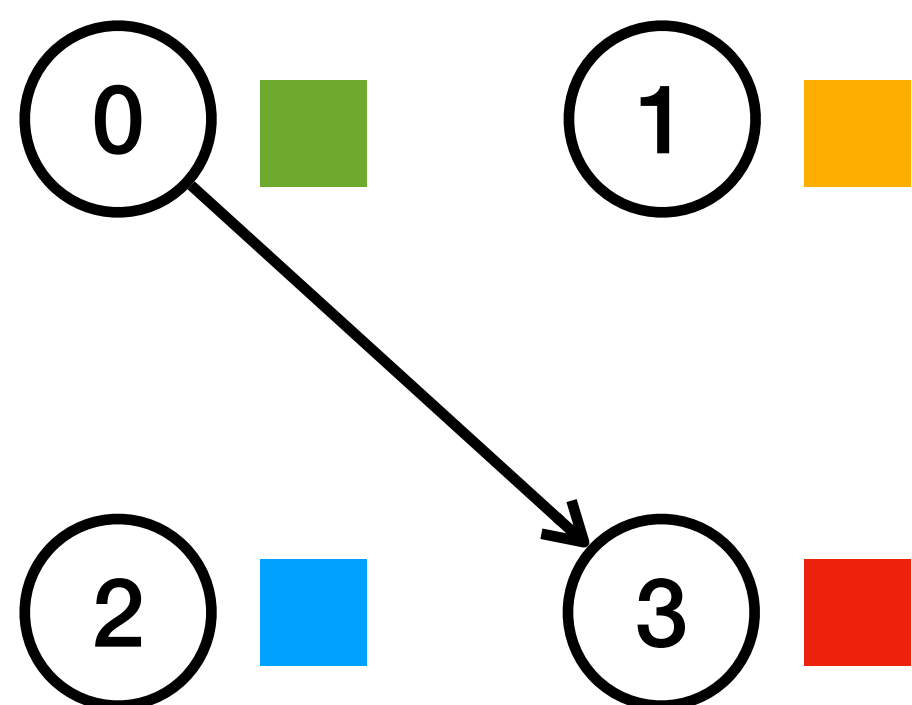
When number of workers is large 😭

The bandwidth requirement of parameter server grows linearly w.r.t number of workers.

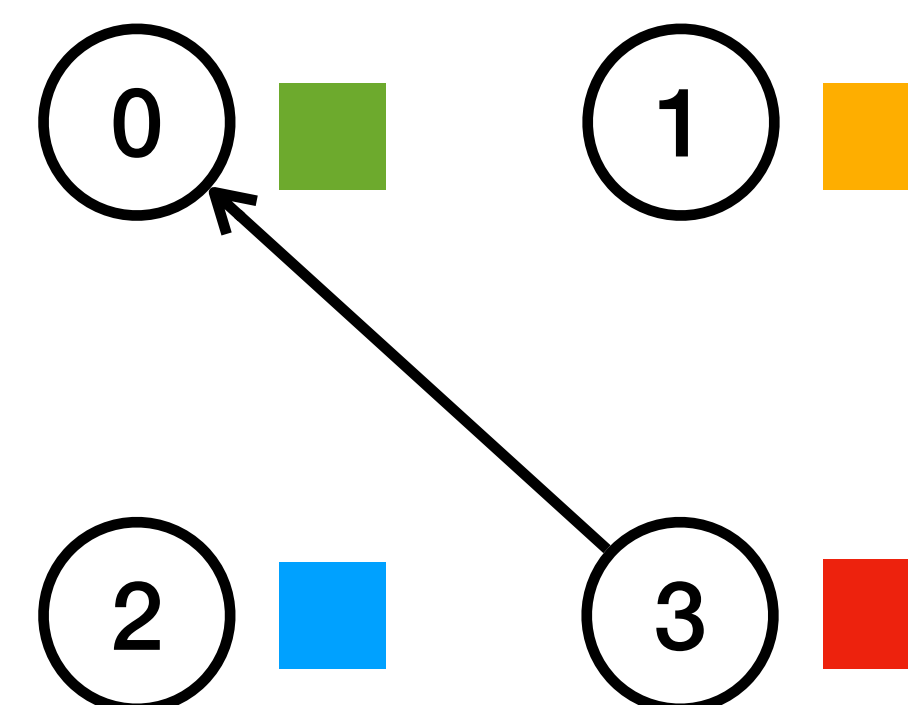
Distributed Communication

Point-to-Point: Send and Recv

Send: n0 -> n3



Recv: n0 -> n3



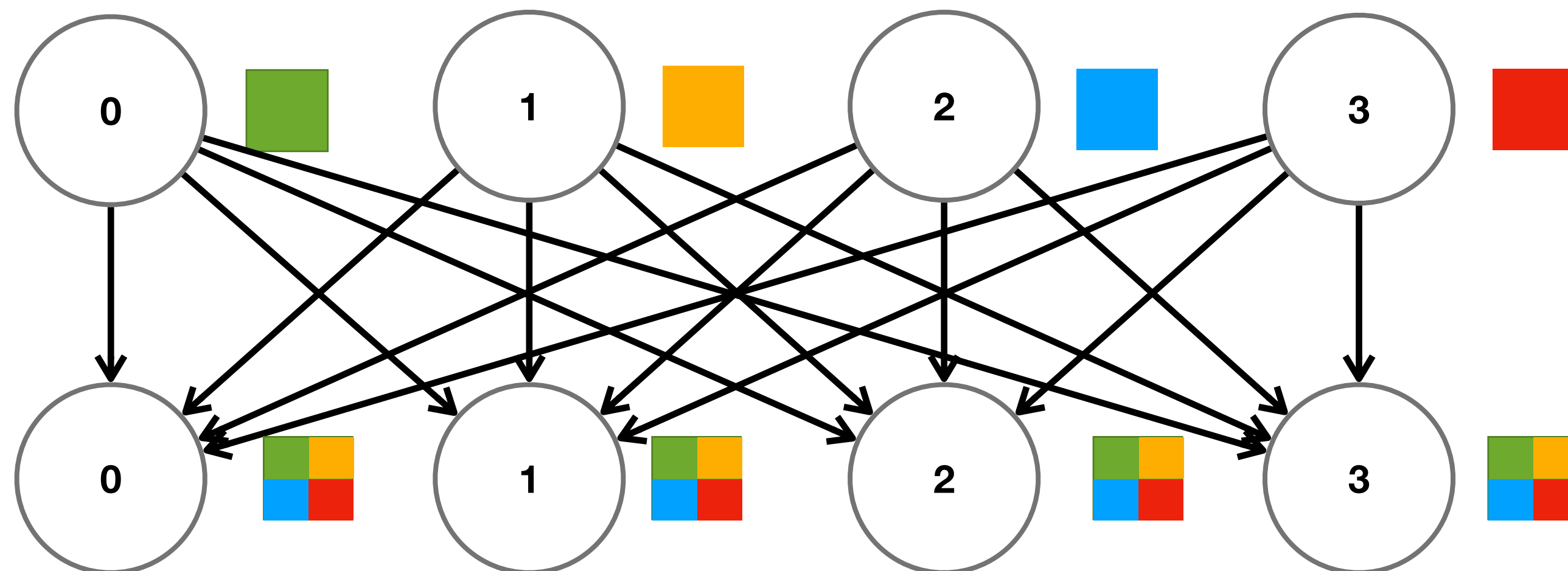
Point-to-point communication: transfer data from one process to another

- Send & Receive are the most common distributed communication schemes.
- Implemented in Socket / MPI / Gloo / NCCL

Distributed Communication

Naive All-Reduce Implementation - Parallel Reduce

Step 1



Pseudocode:

```
-----  
Parallel for i:=0 to N:  
    Allreduce(work[i])
```

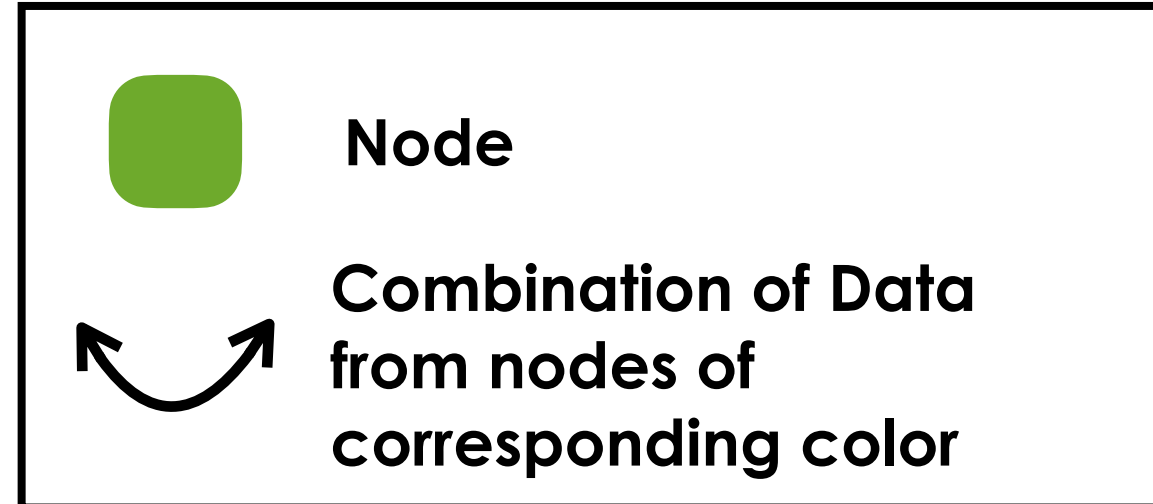
Time: $O(1)$ <- improved

Bandwidth: $O(N^2)$ <- worse

Perform **ALL** reduce operations simultaneously.

Distributed Communication

Recursive Halving All Reduce



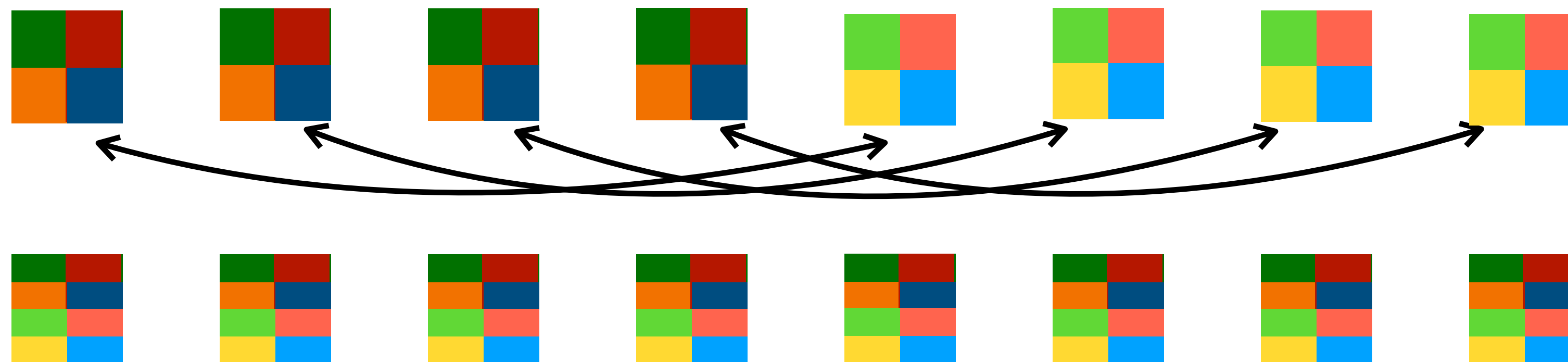
Step 1 - Each node exchanges with neighbors with offset 1



Step 2 - Each node exchanges with neighbors with offset 2



Step 3 - Each node exchanges with neighbors with offset 4



For N workers, AllReduce finish in **$\log(N)$** steps.

[1] Thakur, Rajeev, Rolf Rabenseifner, and William Gropp. "Optimization of collective communication operations in MPICH."

Distributed Communication

All Reduce Implementations Comparison

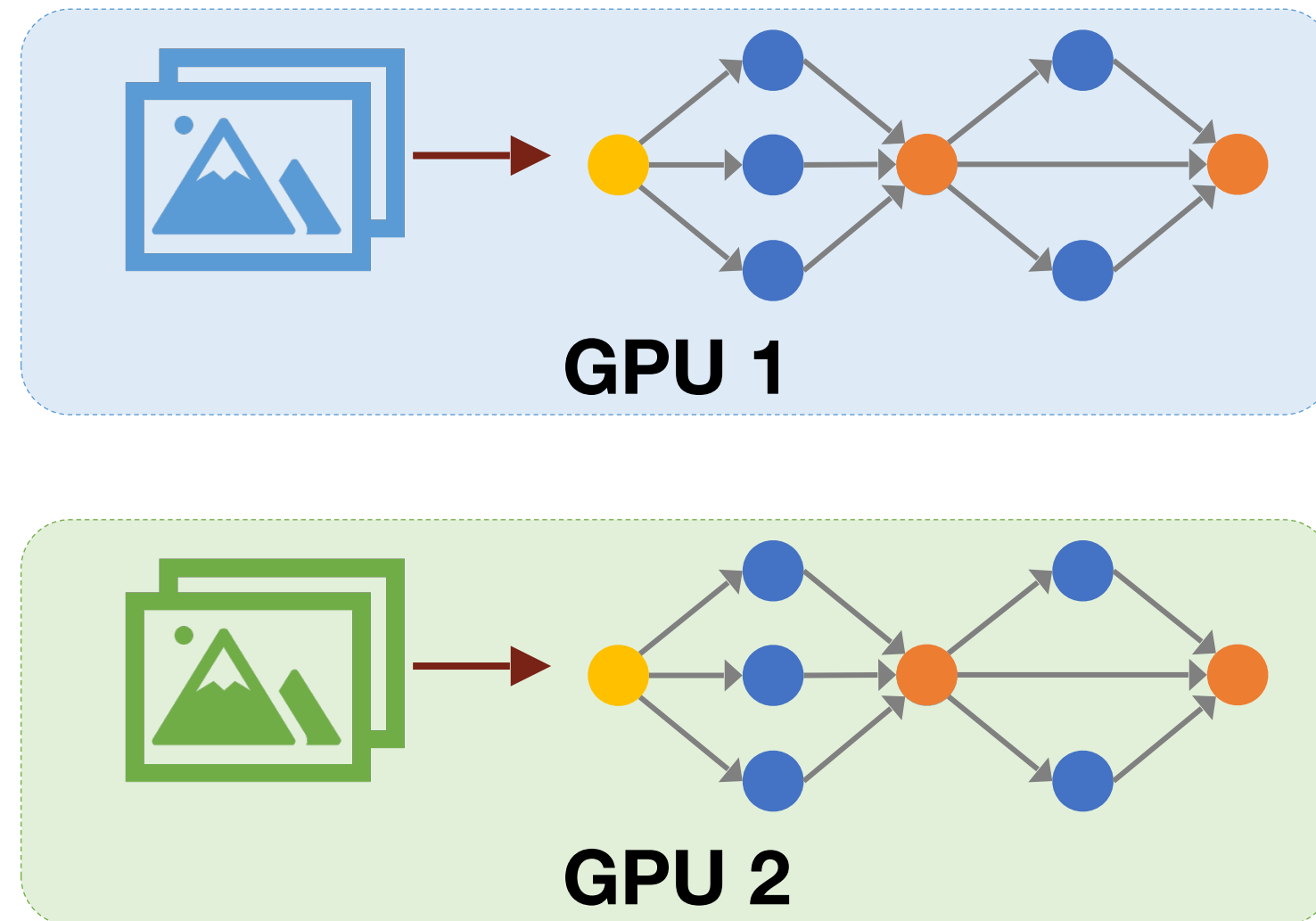
	Time	Peak Node Bandwidth	Total Bandwidth
Parameter Server	$O(1)$	$O(N)$	$O(N)$
All-Reduce - Sequential	$O(N)$	$O(N)$	$O(N)$
All-Reduce - Ring	$O(N)$	$O(1)$	$O(N)$
All-Reduce - Parallel	$O(1)$	$O(N)$	$O(N^2)$
All-Reduce - Recursive Halving	$O(\lg N)$	$O(1)$	$O(N)$

AllReduce with proper implementations reduce the peak bandwidth from $O(N)$ to $O(1)$ with little time overhead.

Parallelism in Distributed Training

- Data Parallelism
- **Model Parallelism**
- Compare the Advantages and Disadvantages of Two Parallelism

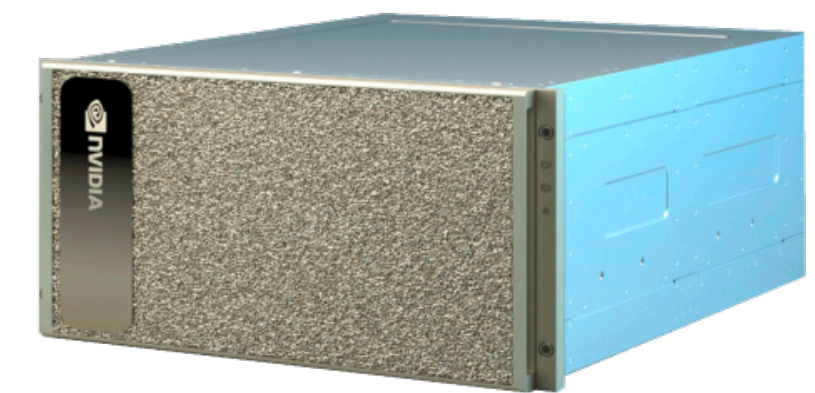
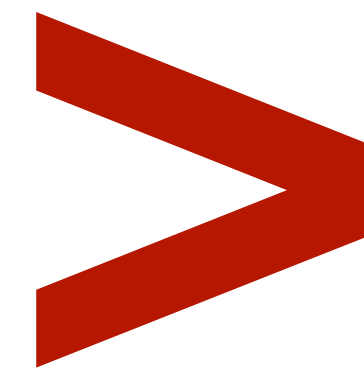
Data Parallelism Cannot Train Large Models



Though model parallelism has better device utilization, if train a super-large model (e.g., GPT-3)



175B * 16 Bits
= 350GB Memory



Nvidia A100 80GB

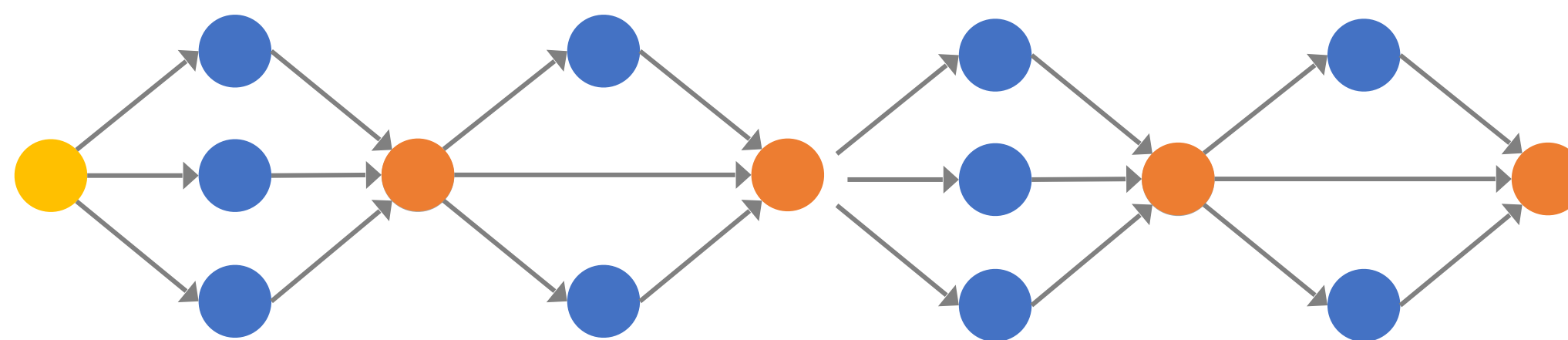
Even the best GPU **CANNOT** fit the model into memory!

Introduction to Distributed Training

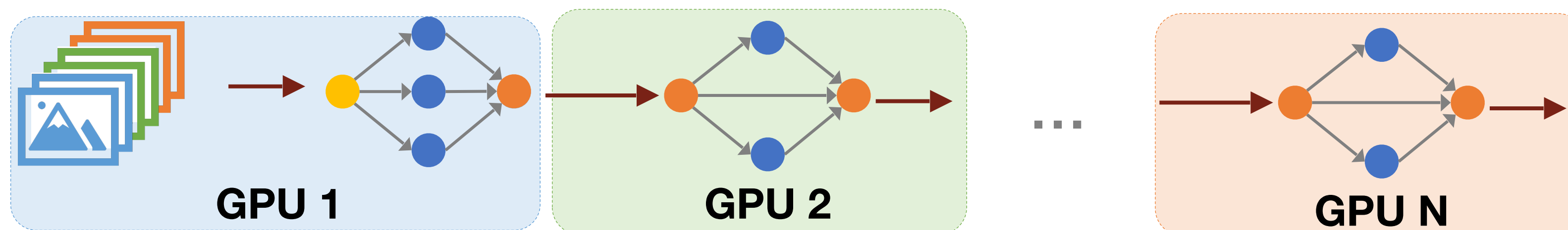
Model Parallelism



Training Dataset



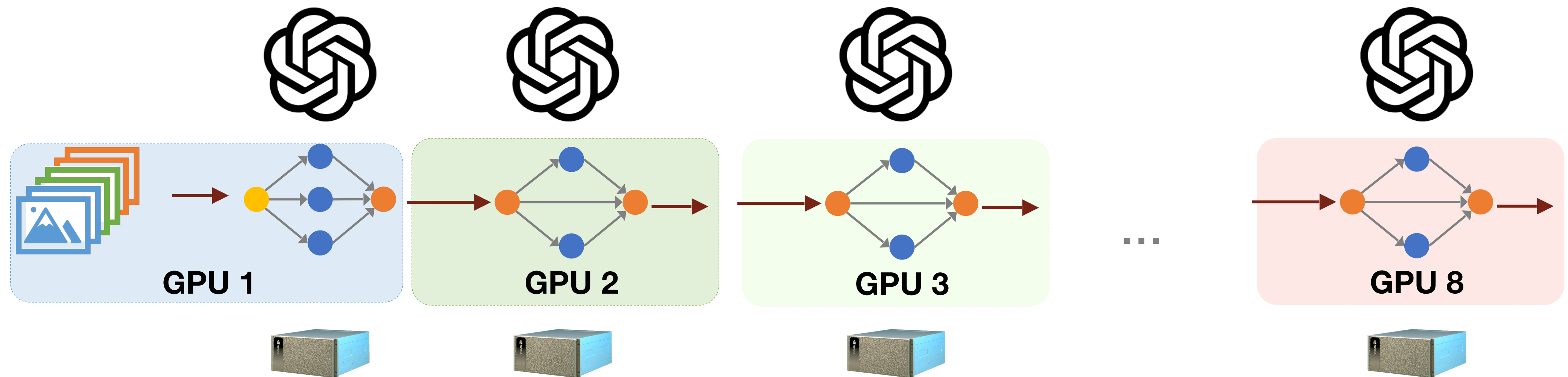
ML Model



Figures credit from CMU 15-849 [Jia 2022]

Model Parallelism Designed for Large Model Training

In order to fit training into hardware, instead of splitting the data, model parallelism split the model

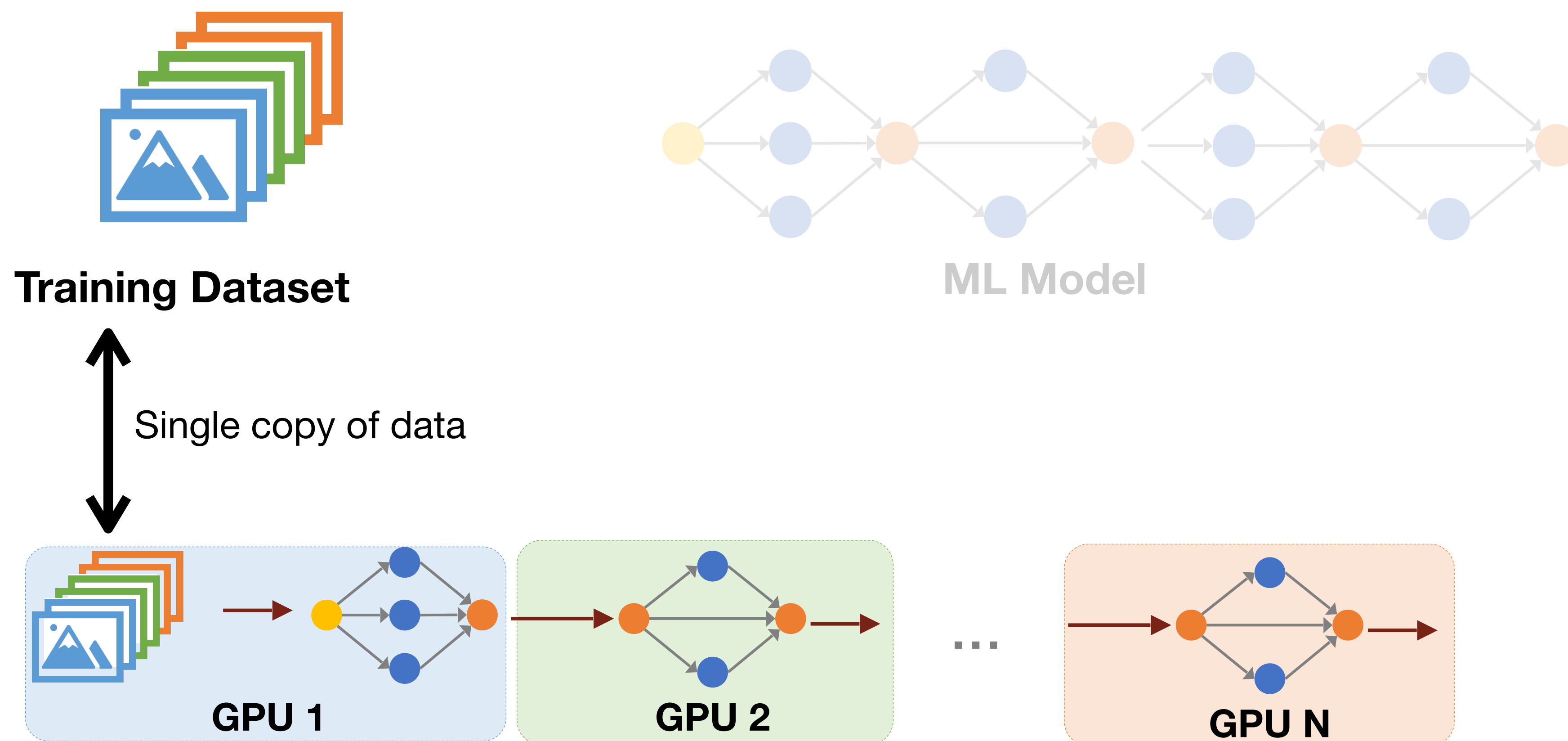


$$350\text{GB} / 8 \text{ cards} = 43.75\text{G} < 80\text{G}$$

With model parallelism, large ML models can be placed and trained on GPUs.

Introduction to Distributed Training

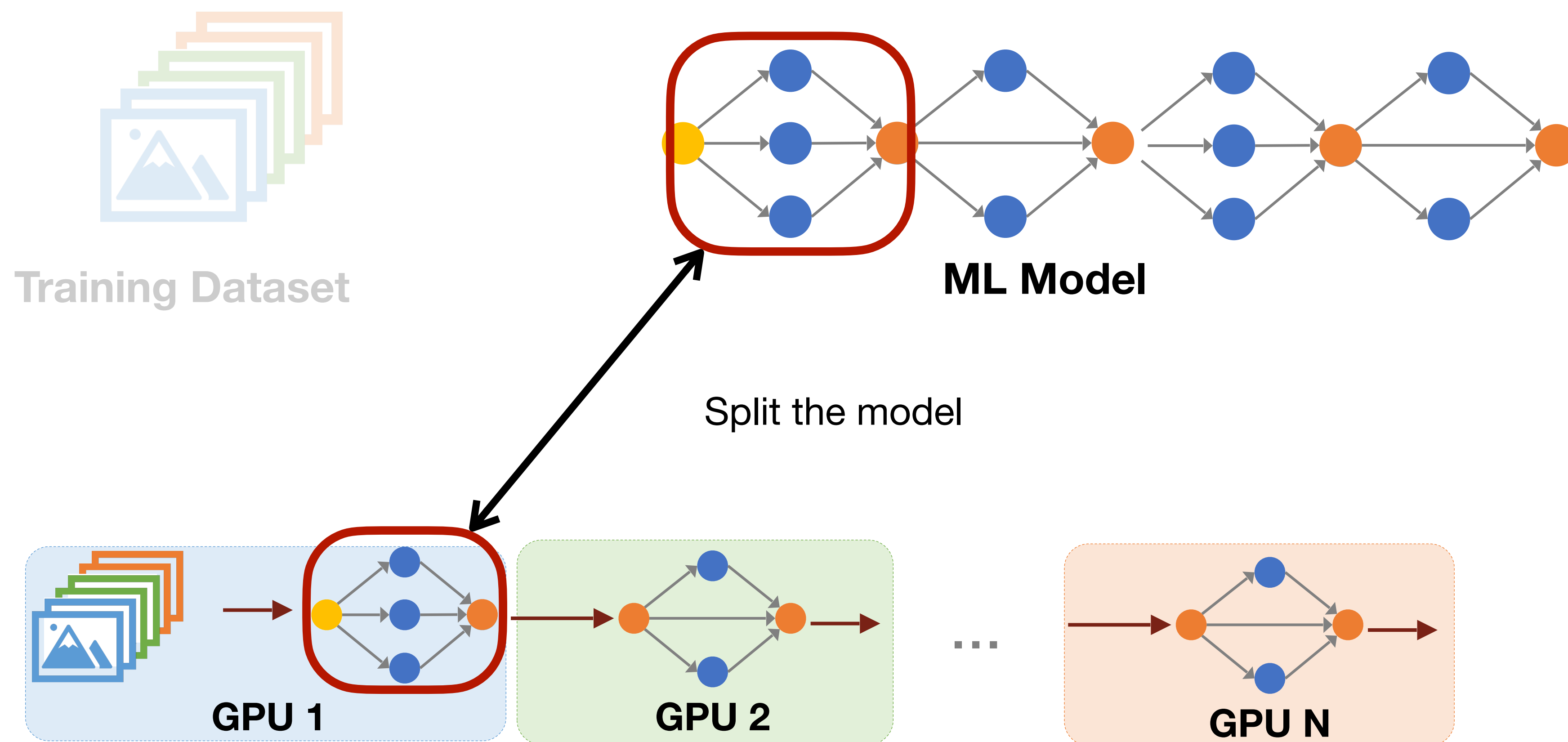
Model Parallelism



Figures credit from CMU 15-849 [Jia 2022]

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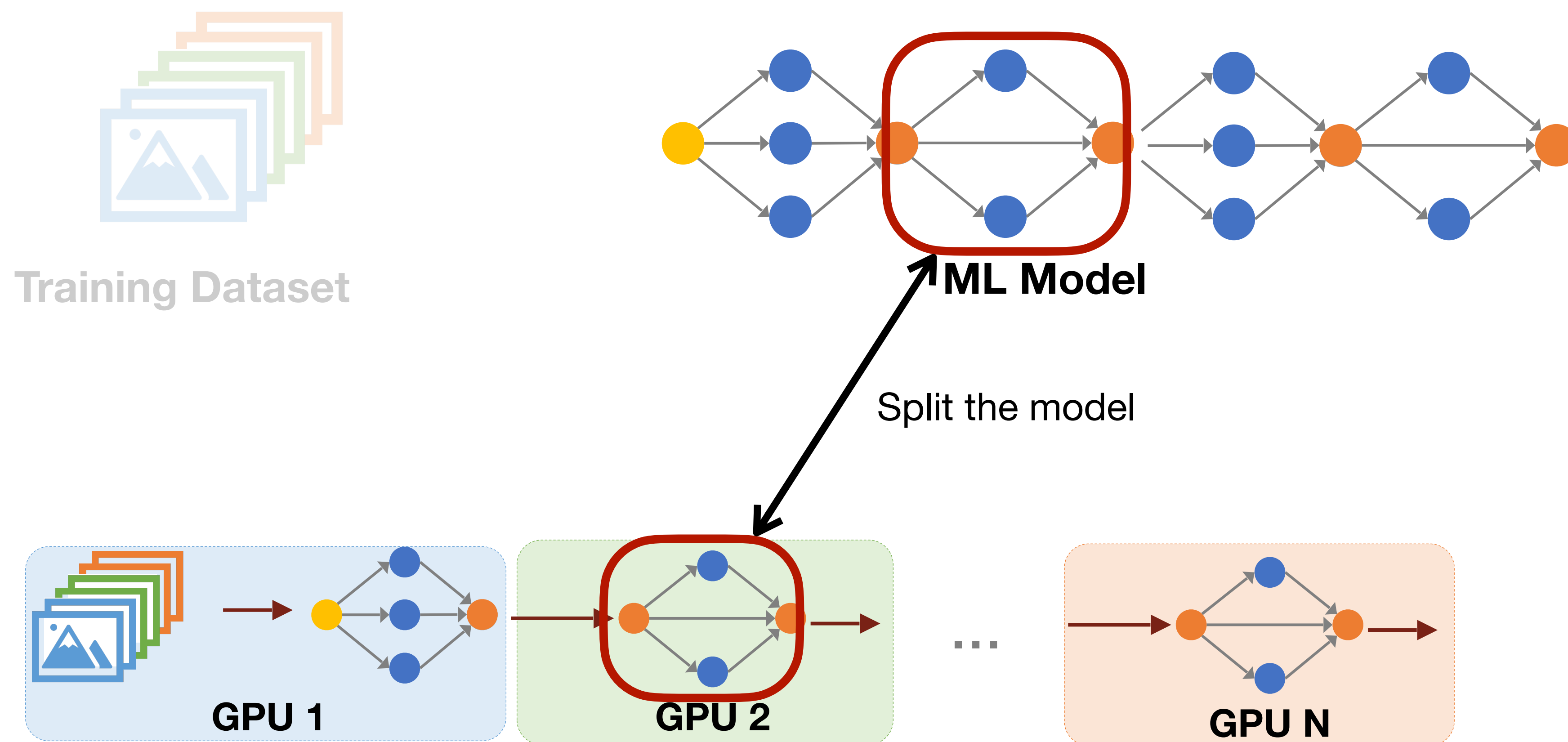
Model Parallelism



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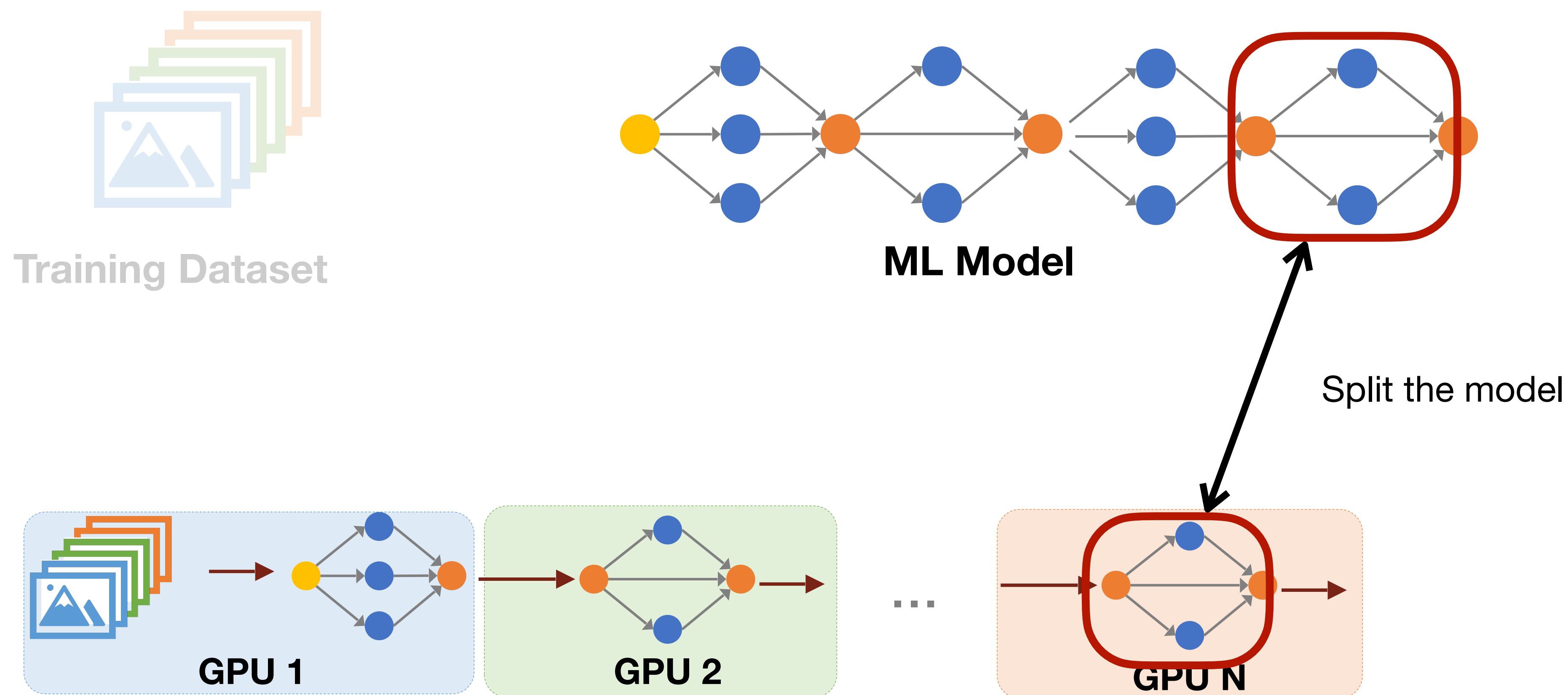
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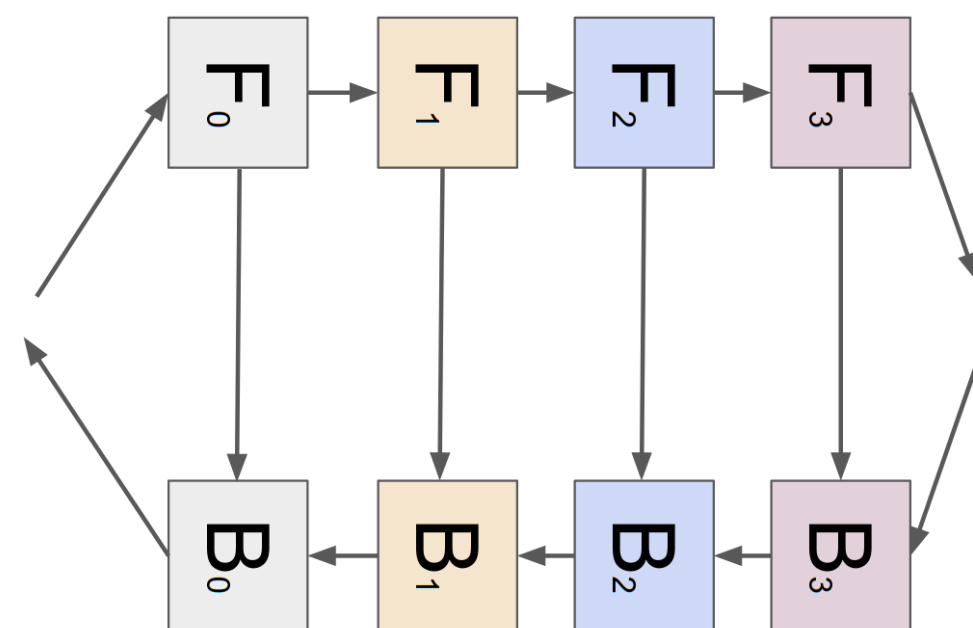
Model Parallelism



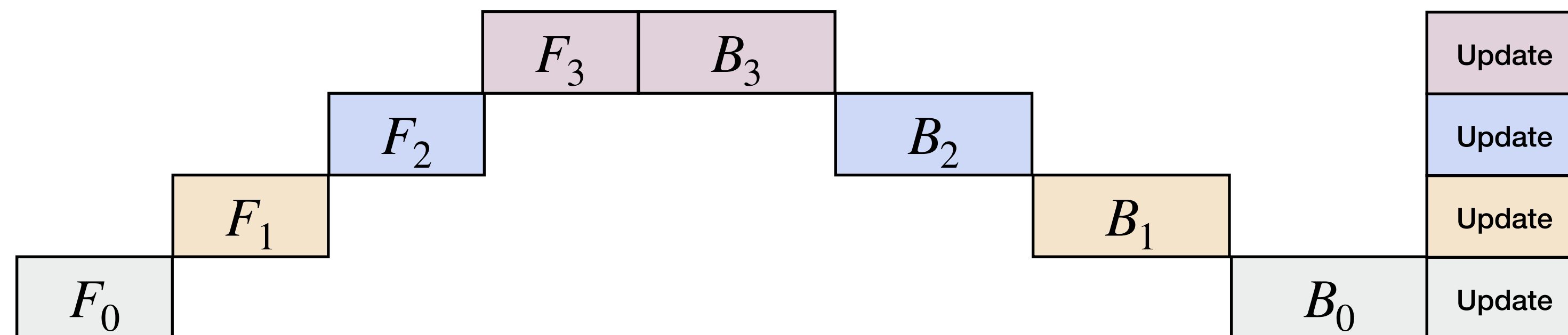
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Model Parallelism Workflow

Naive Implementation



(a). Training data flow



(b). Training timeline

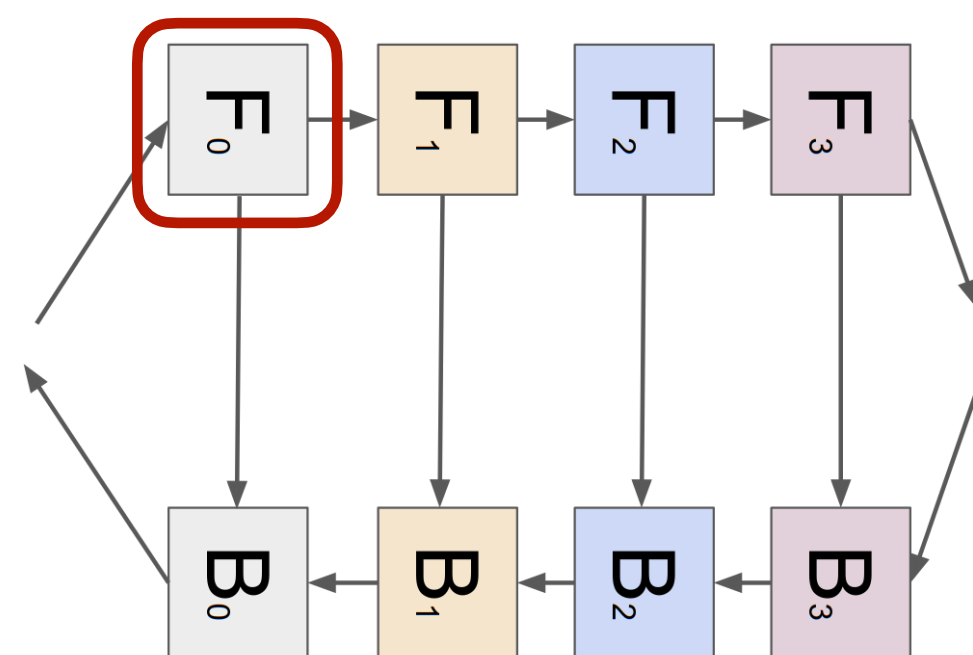
F: Forward B: Backward. Train a 4 layer network with model parallelism.

Model parallelism is needed for training a bigger DNN model on accelerators by dividing the model into partitions and assigning different partitions to different accelerators.

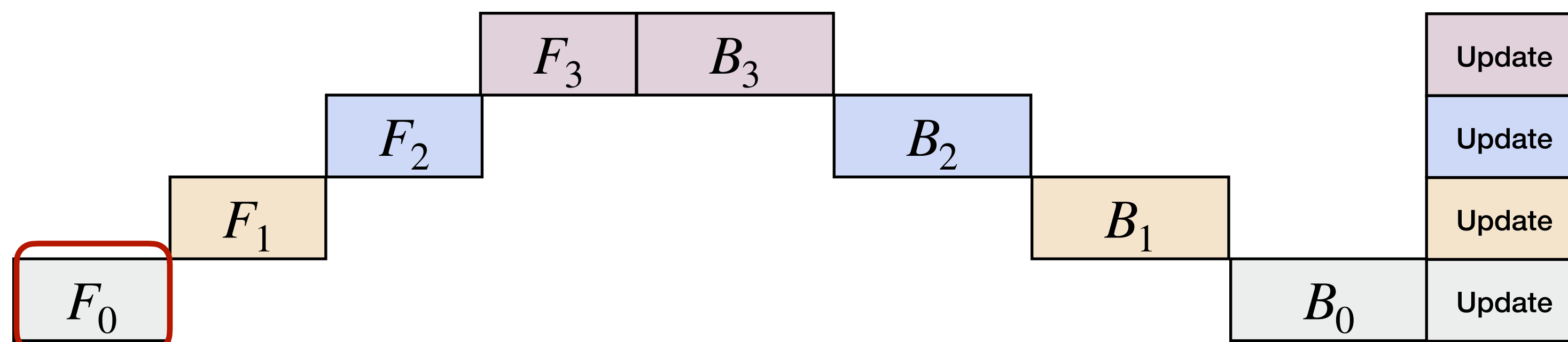
GPipe: Efficient Training of Giant Neural Networks using Pipeline Parallelism [Huang et al. 2018]

Model Parallelism Workflow

Naive Implementation



(a). Training data flow



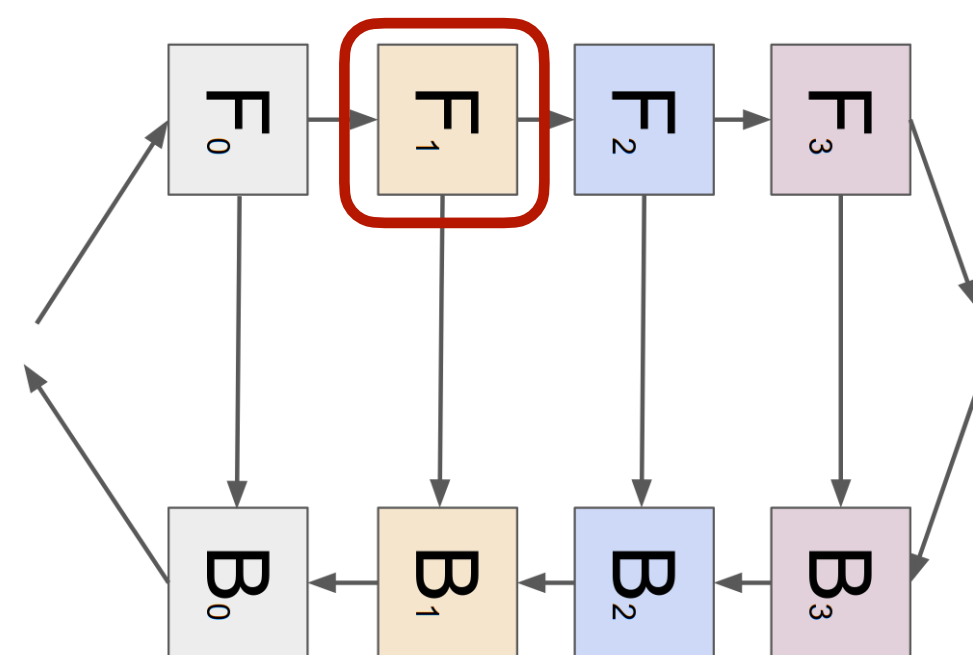
(b). Training timeline

F: Forward B: Backward. Train a 4 layer network with model parallelism.

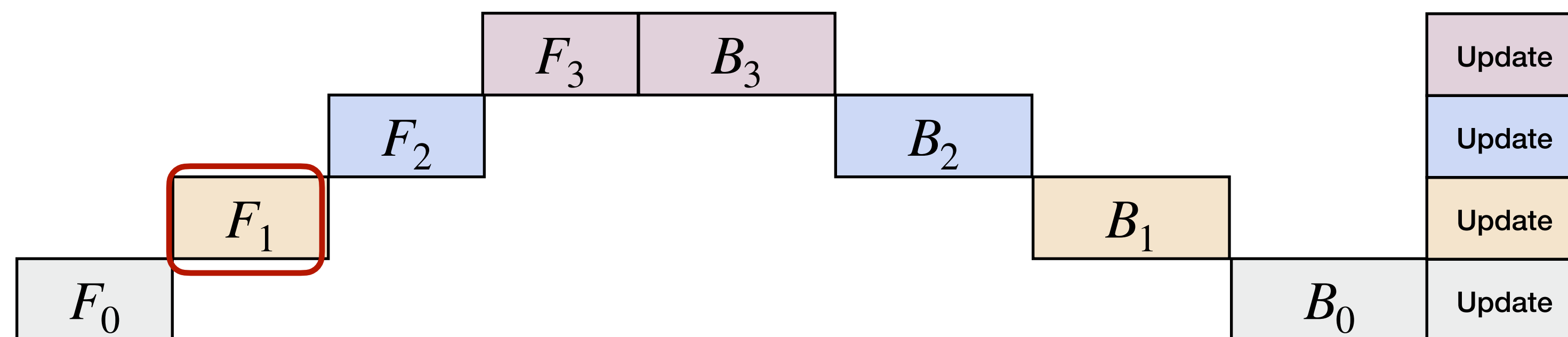
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Model Parallelism Workflow

Naive Implementation



(a). Training data flow



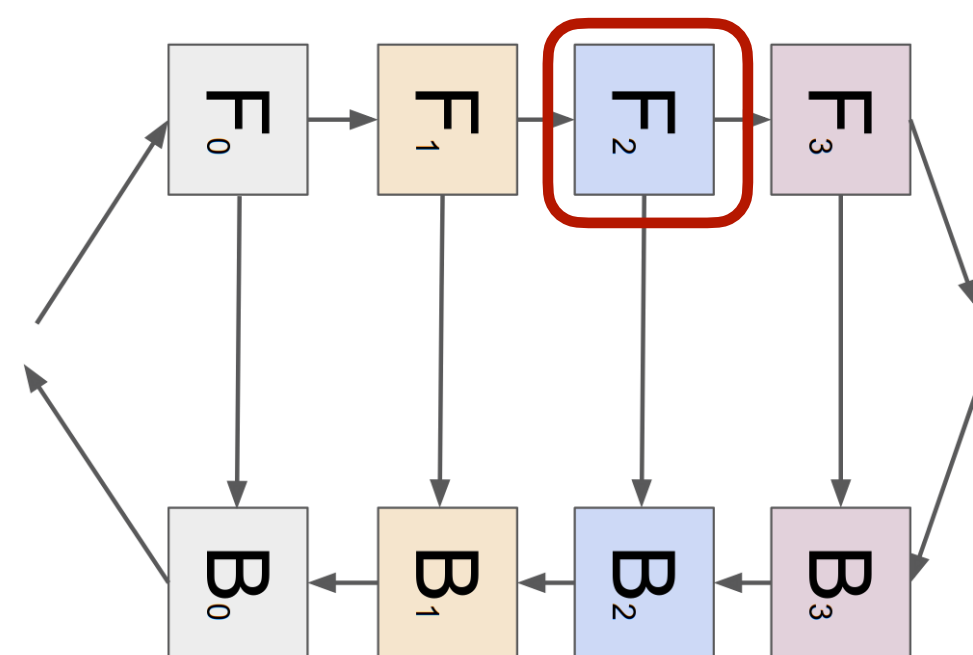
(b). Training timeline

F: Forward B: Backward. Train a 4 layer network with model parallelism.

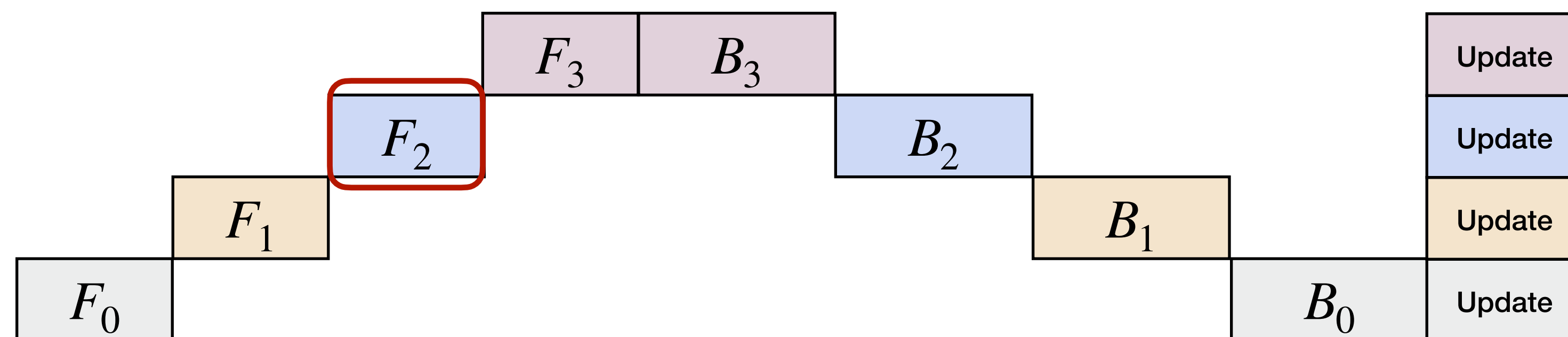
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Model Parallelism Workflow

Naive Implementation



(a). Training data flow



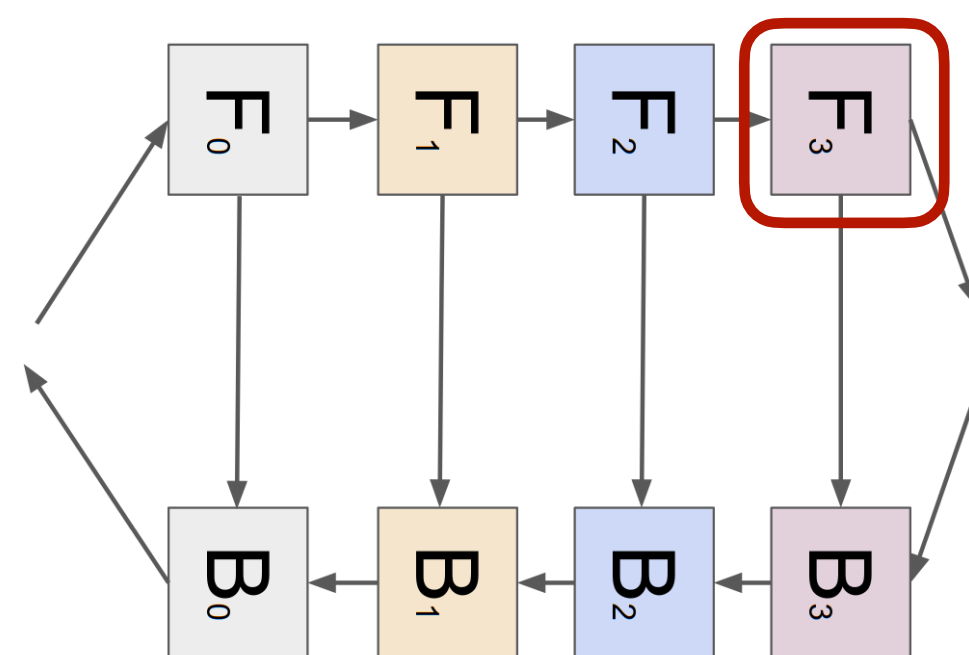
(b). Training timeline

F: Forward B: Backward. Train a 4 layer network with model parallelism.

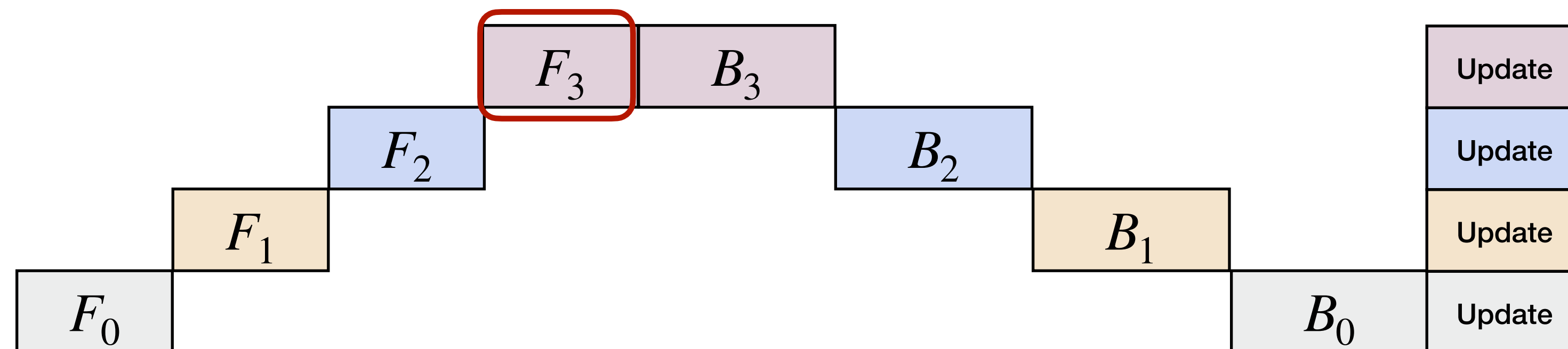
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Model Parallelism Workflow

Naive Implementation



(a). Training data flow



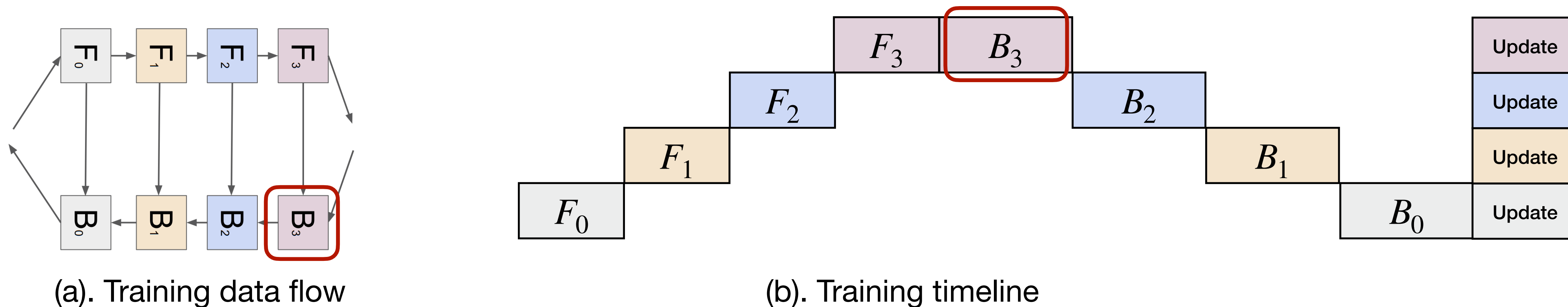
(b). Training timeline

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Model Parallelism Workflow

Naive Implementation

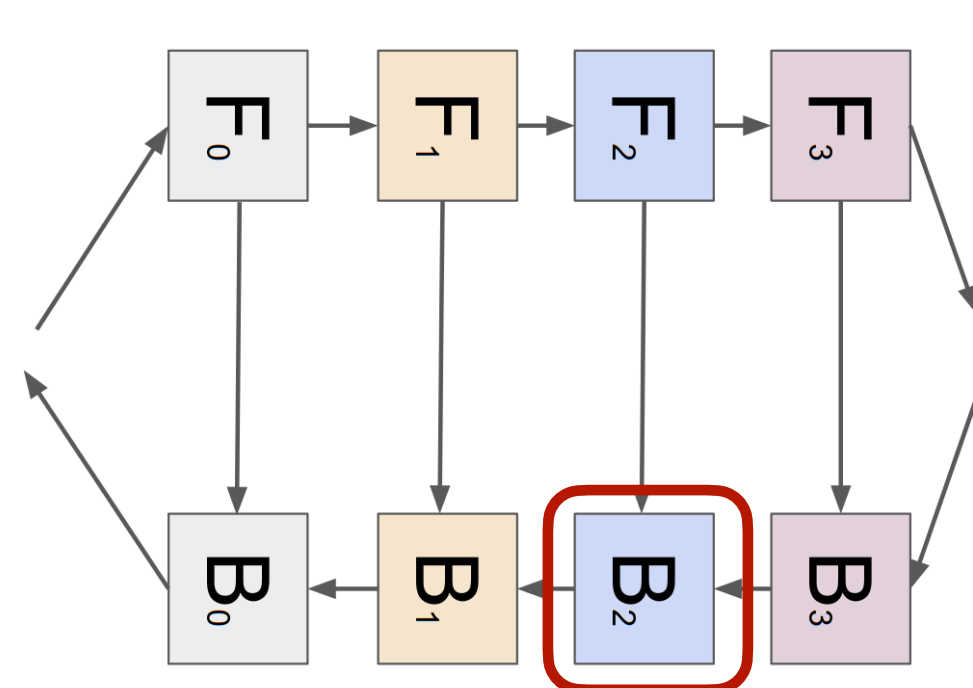


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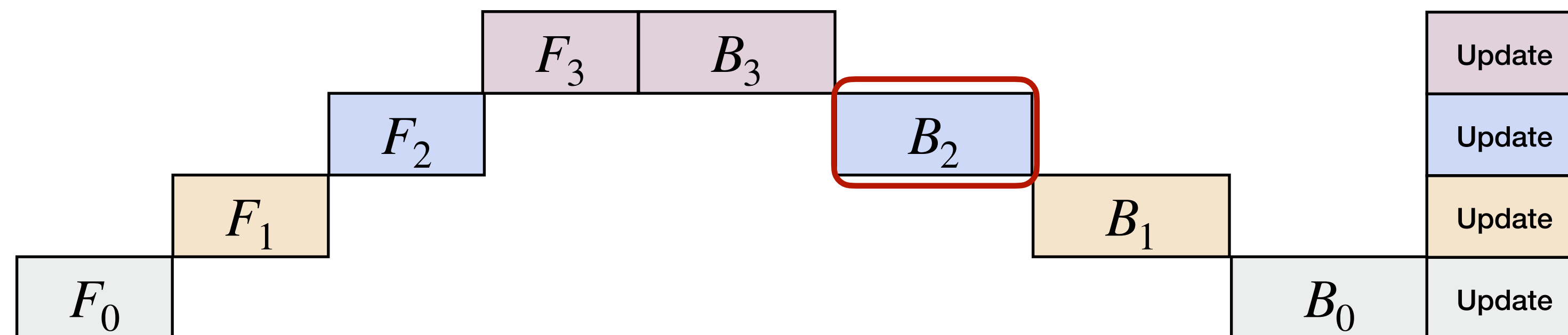
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Model Parallelism Workflow

Naive Implementation



(a). Training data flow



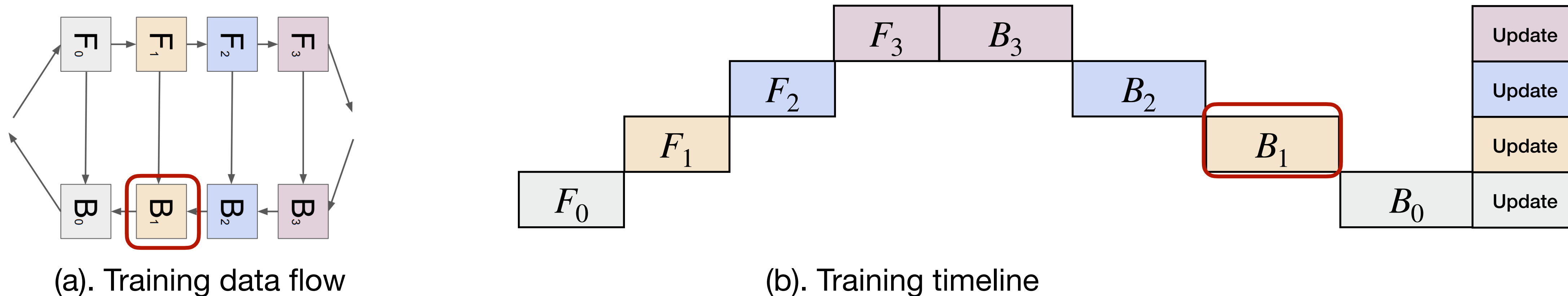
(b). Training timeline

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Model Parallelism Workflow

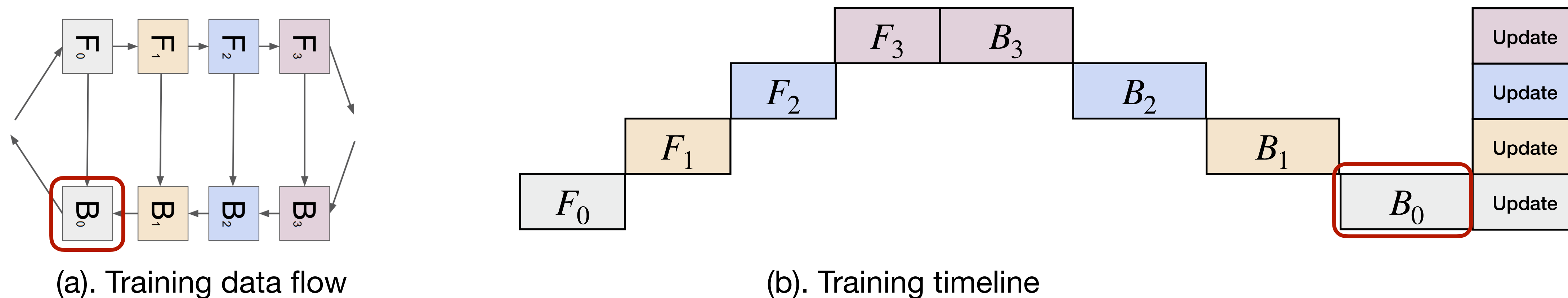
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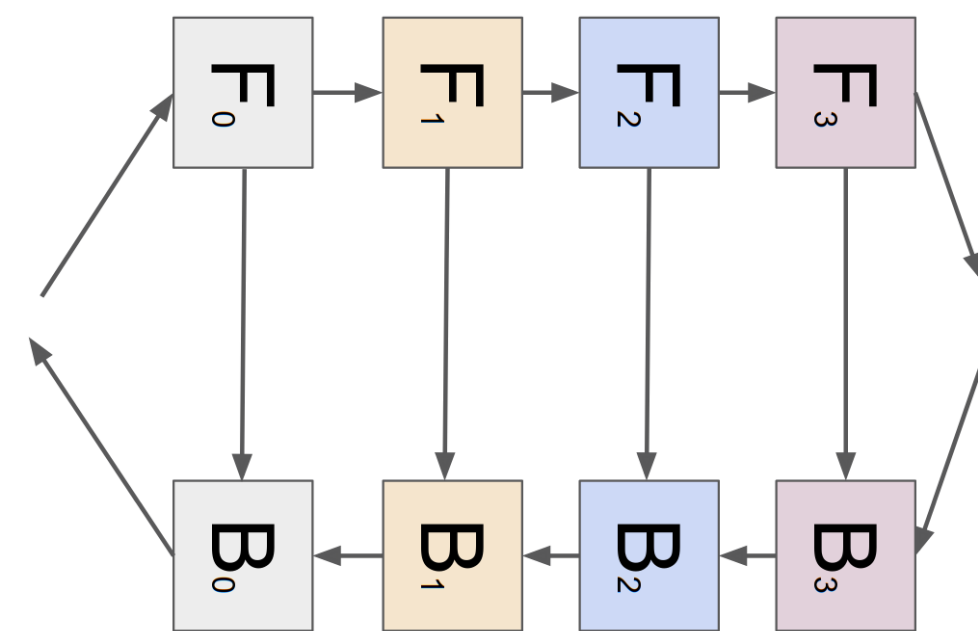
Naive Implementation



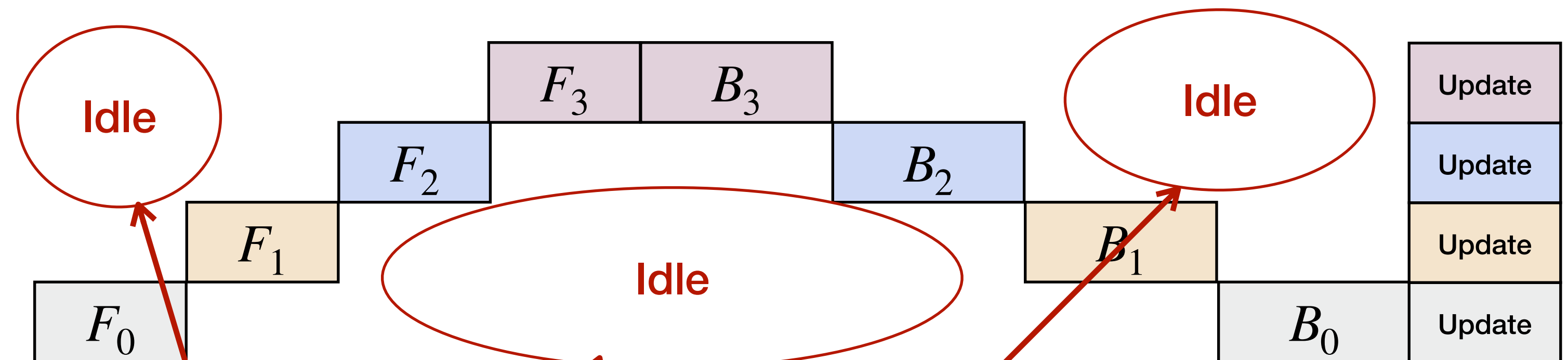
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Model Parallelism Workflow



(a). Training data flow



(b). Training timeline

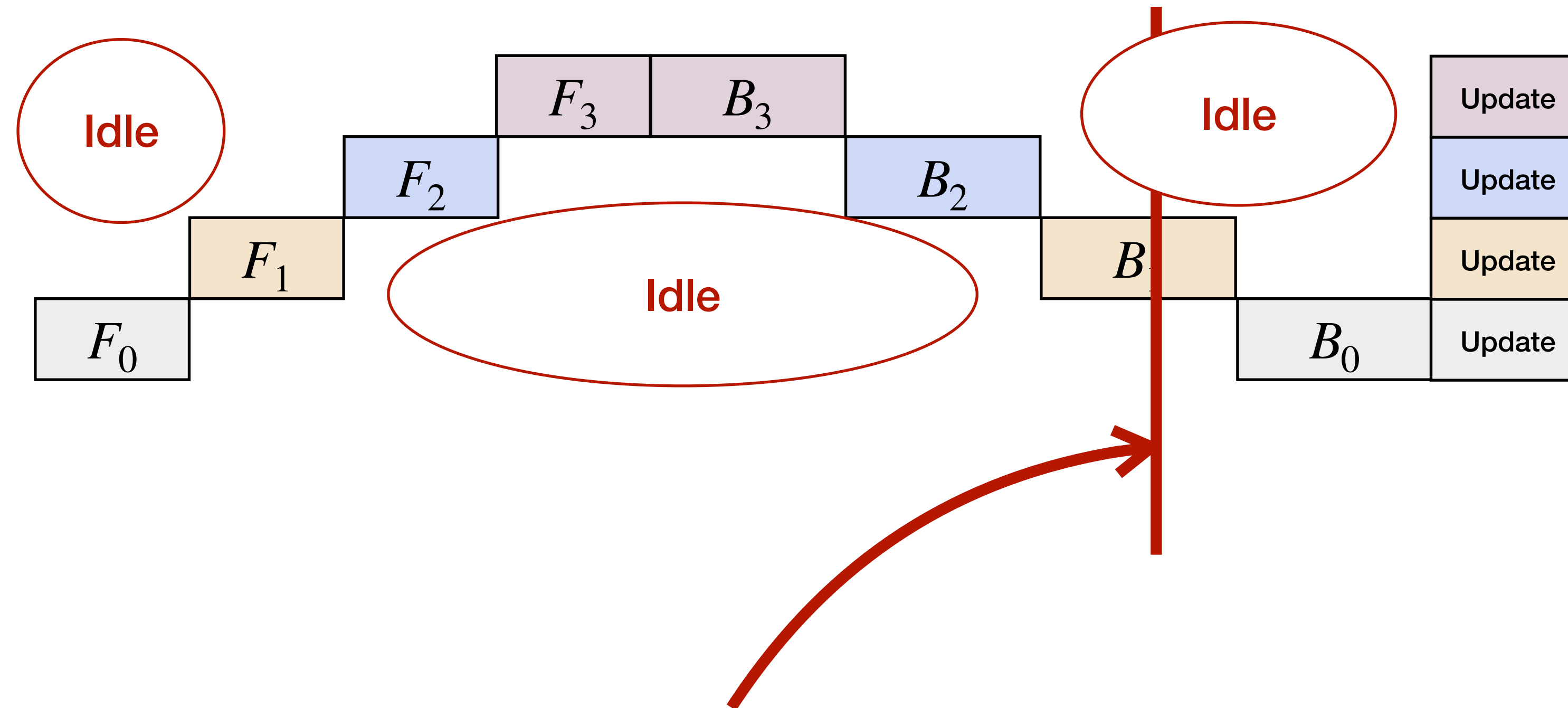
F: Forward B: Backward. Train a 4 layer network with model parallelism.

Model parallelism is needed for training a bigger DNN model on accelerators by dividing the model into partitions and assigning different partitions to different accelerators.

But accelerators are significantly **under-utilized** during model parallelism!

GPipe: Efficient Training of Giant Neural Networks using Pipeline Parallelism [Huang et al. 2018]

Naive Model Parallelism Suffers from Utilization



Only one device is computing at a time and others are waiting for it.

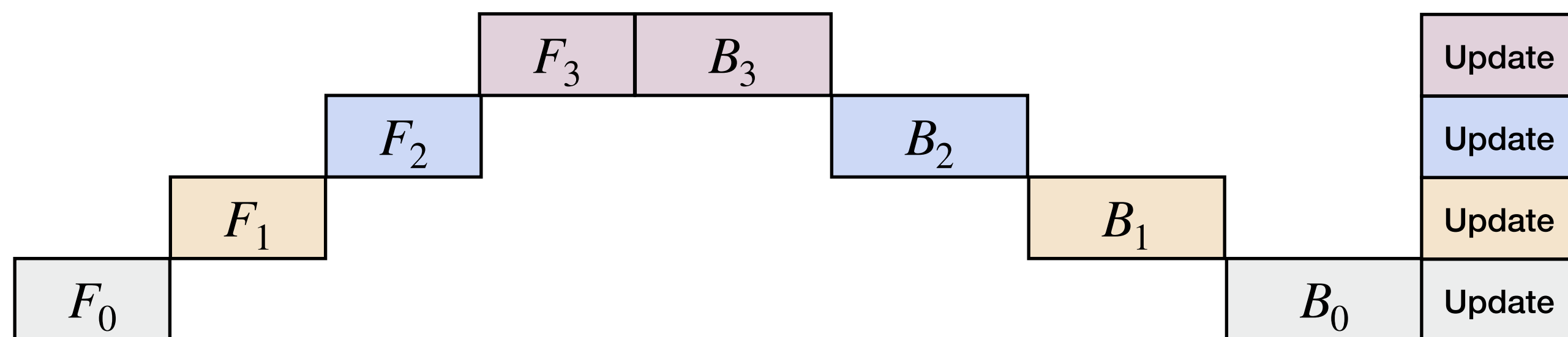
Theoretical utilization: 25% (**low!**)

Usual data parallelism utilization: ~75%

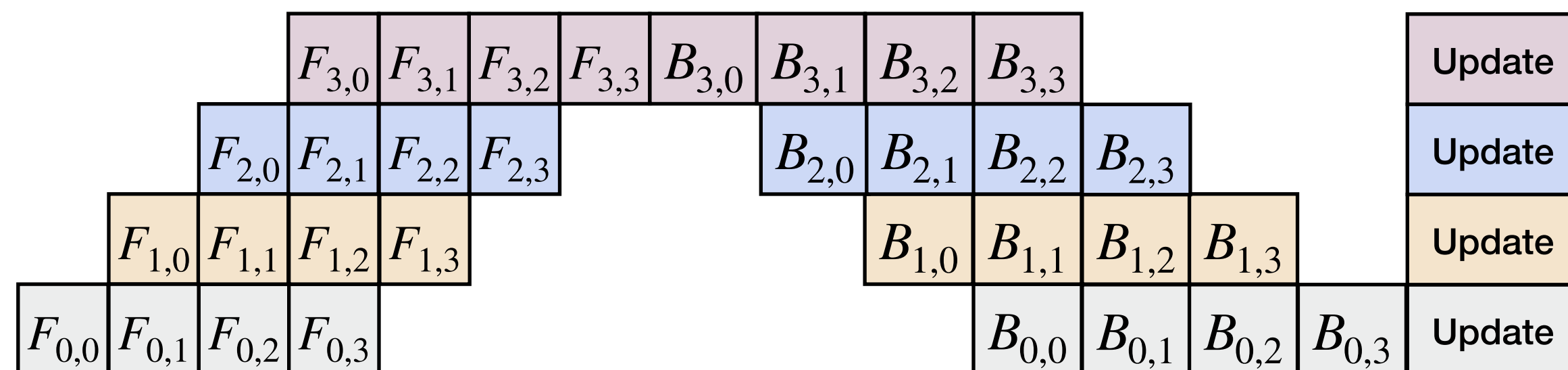
GPipe: Efficient Training of Giant Neural Networks using Pipeline Parallelism [Huang et al. 2018]

Pipeline Parallelism

Gpipe: *Easy Scaling with Micro-Batch Pipeline Parallelism*



(a). Naive model parallelism

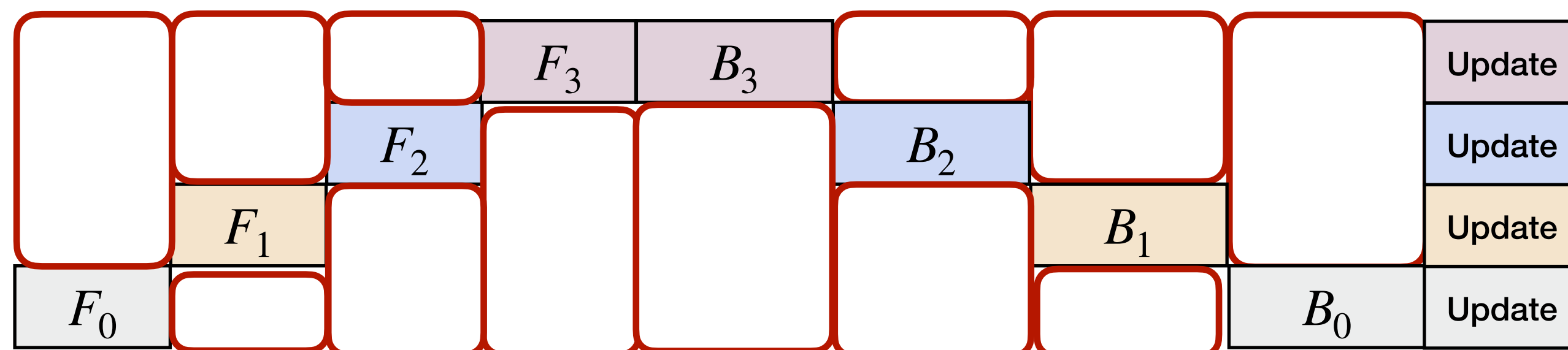


(b). Pipeline parallelism

- Split a single batch to micro batches
 - $[16, 10, 512] \rightarrow$
 - $[4, 10, 512]$
 - $[4, 10, 512]$
 - $[4, 10, 512]$
 - $[4, 10, 512]$
- Motivation: model parameters are not changed during computation within a batch, thus we can pipeline computation and communication

Pipeline Parallelism

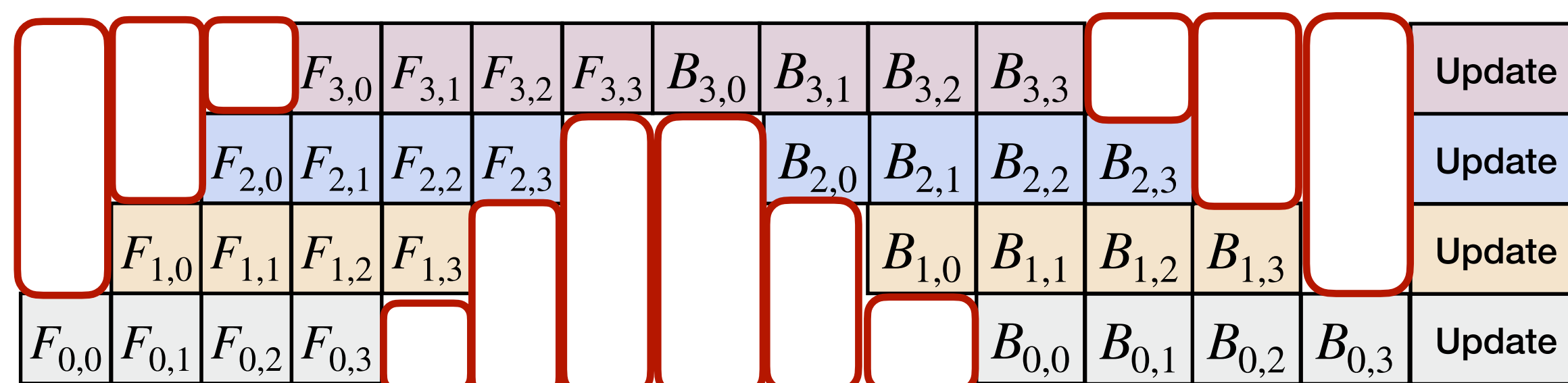
Micro-batch improves the device utilization



(a). Naive model parallelism

Utilization: (25%)

The more chunks (#num of micro batches), the higher of device utilization.



(b). Pipeline parallelism

Utilization: **57%** (2.5x improvement)

GPipe Pipeline Bubbles

- GPipe synchronizes weights at each mini batch
- Pro: maintain the original maths => potentially more efficient SGD
- Con: pipeline bubble => inefficient GPU use

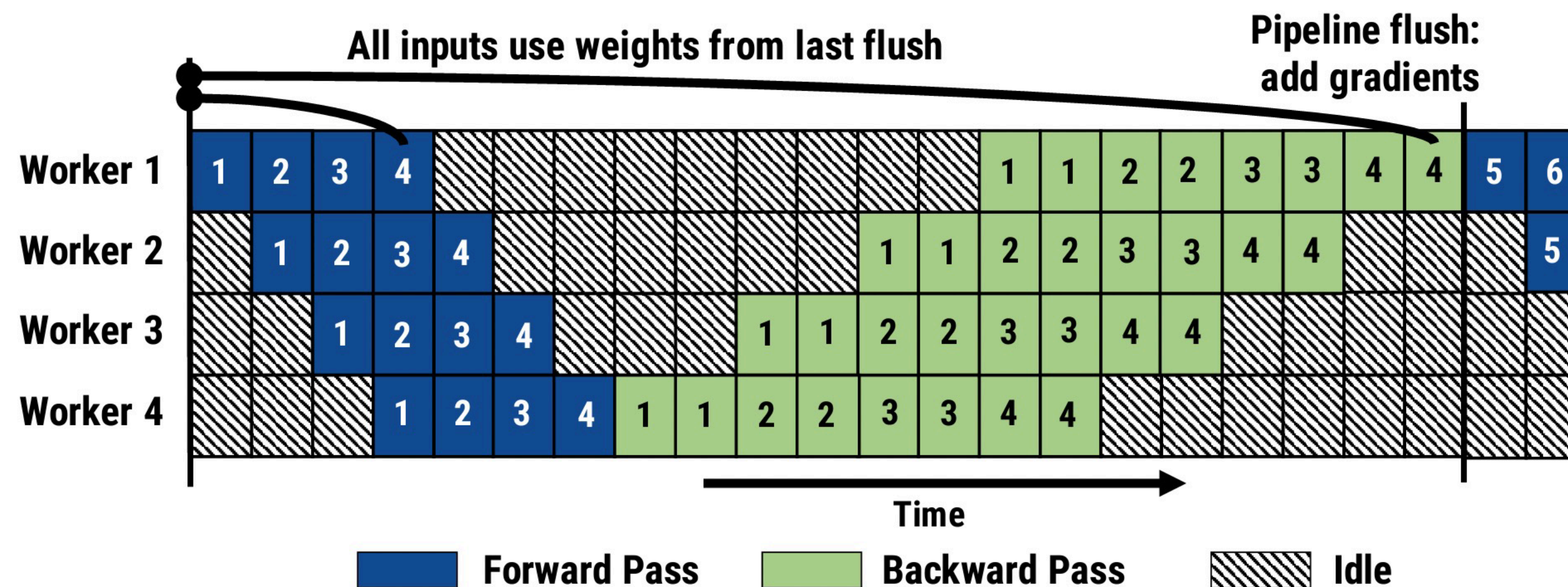
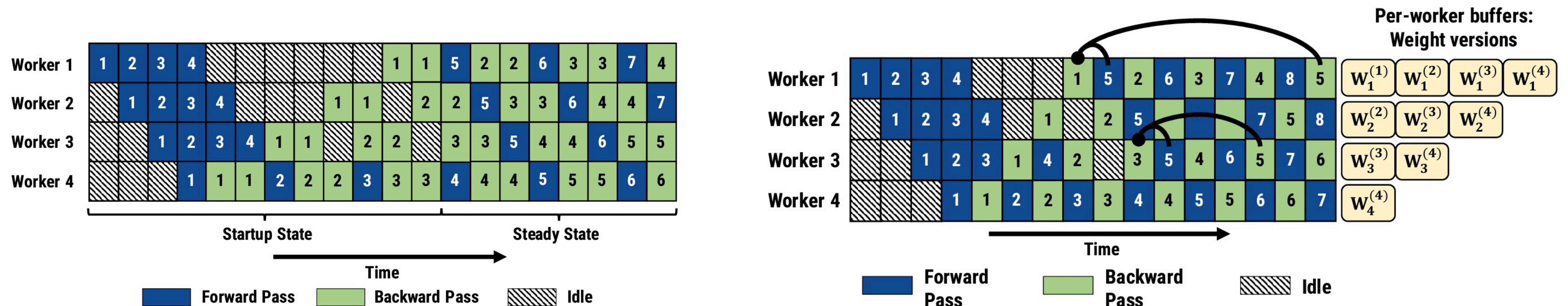


Figure 3: GPipe’s inter-batch parallelism approach. Frequent pipeline flushes lead to increased idle time.

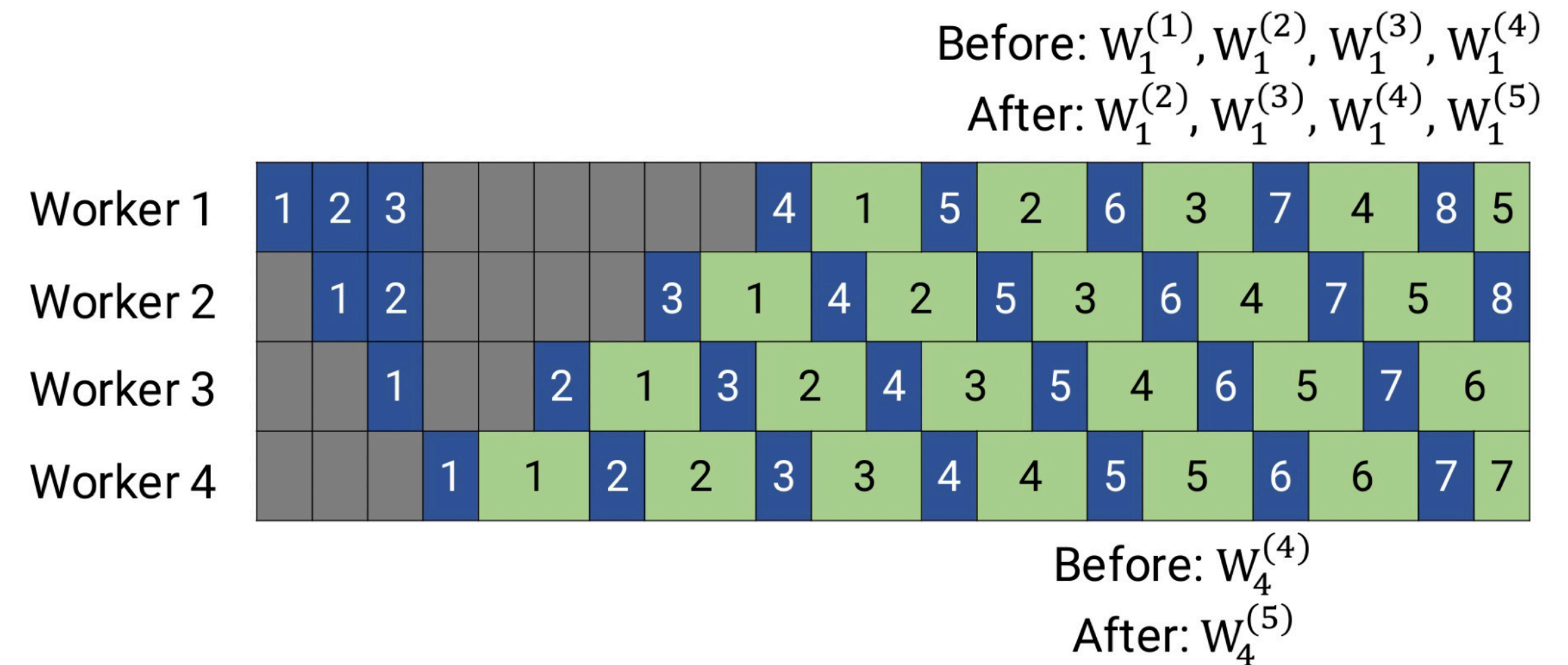
Image from Narayanan eval. “PipeDream: Generalized Pipeline Parallelism for DNN Training” [SOSP 2019]

PipeDream: 1F1B Scheduling

- Workers alternate between forward and backward passes on minibatches
 - Gradients used to update model immediately
 - Storing multiple weight versions so that the backward and forward of the same minibatch
 - Ensuring the same mini batch uses the same weight version across workers for forward and backward
- Pros: no pipeline bubble, very efficient GPU utilization
- Cons: need to store multiple versions of weights (and intermediate results), not the original maths



PipeDream-2BW



- Only saving two versions of weights

Time $\longrightarrow$ Forward Pass Backward Pass

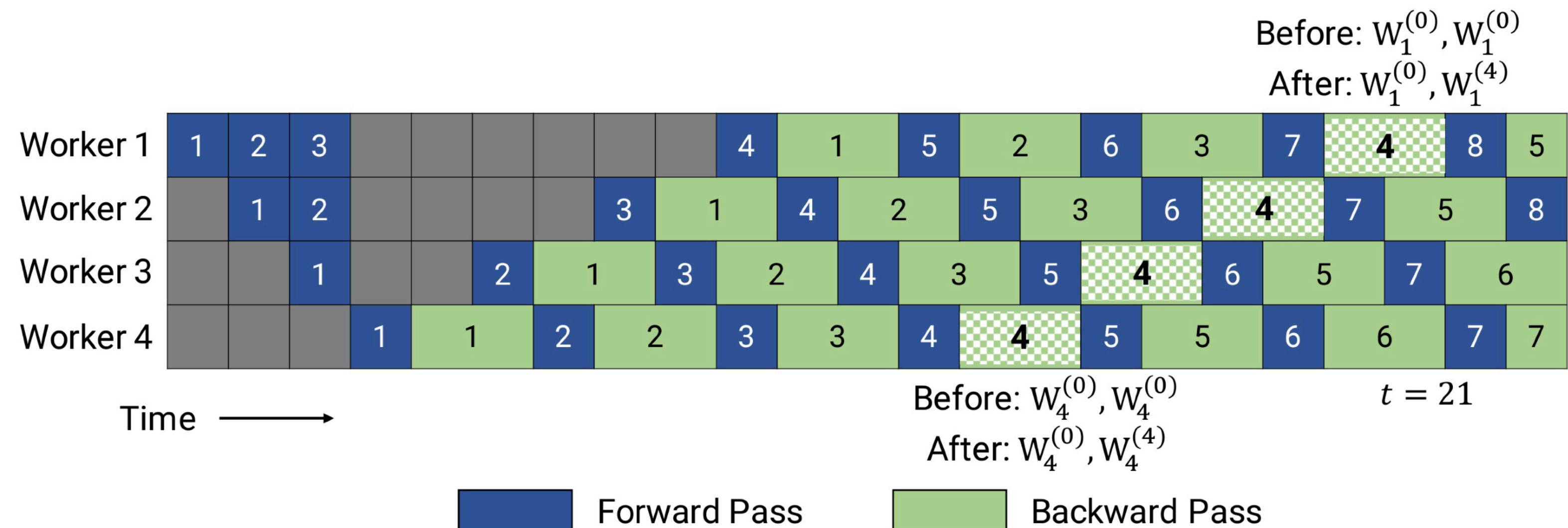
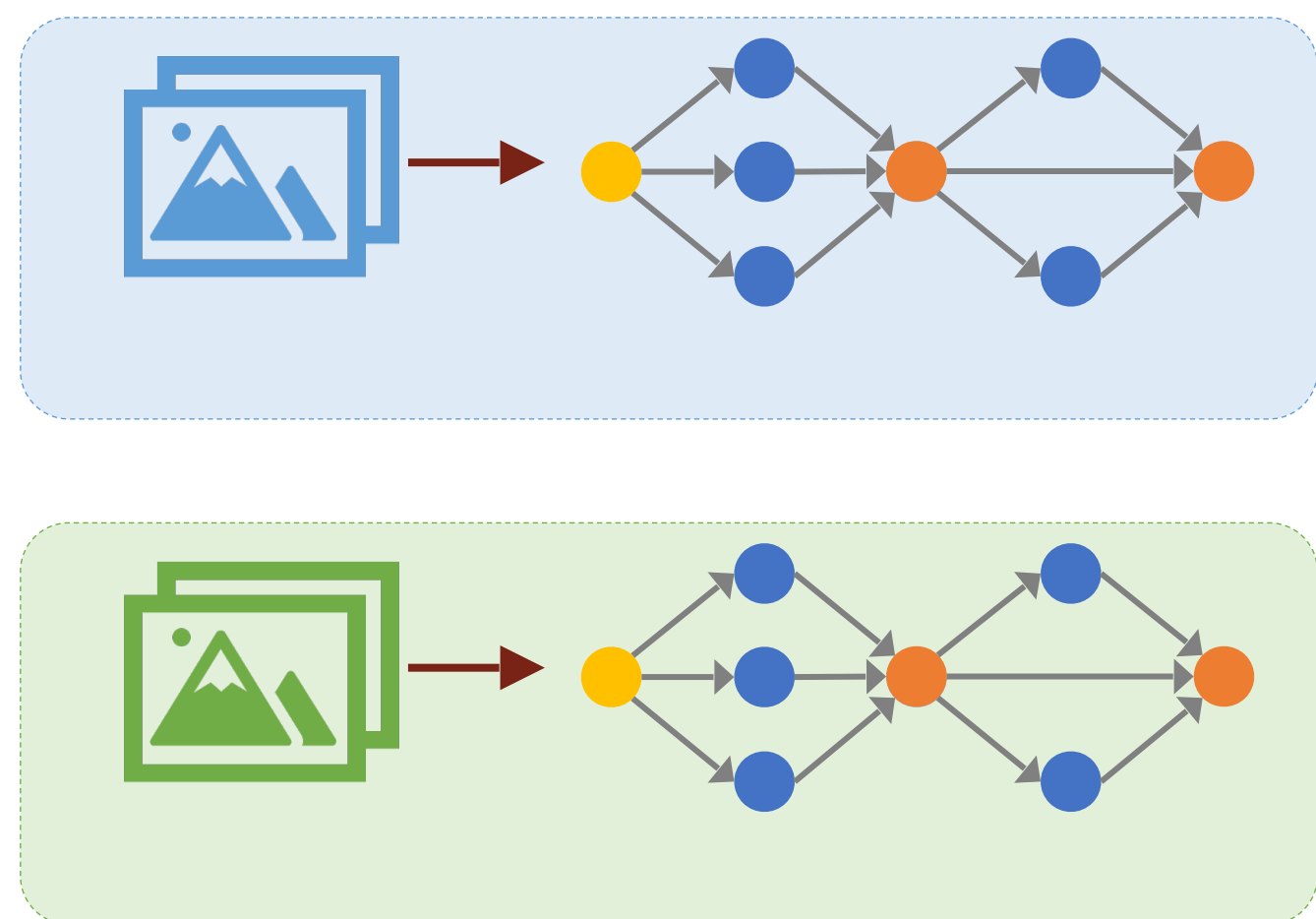


Image from Narayanan et al. "Memory-Efficient Pipeline-Parallel DNN Training" [PMLR 2021]

Parallelism in Distributed Training

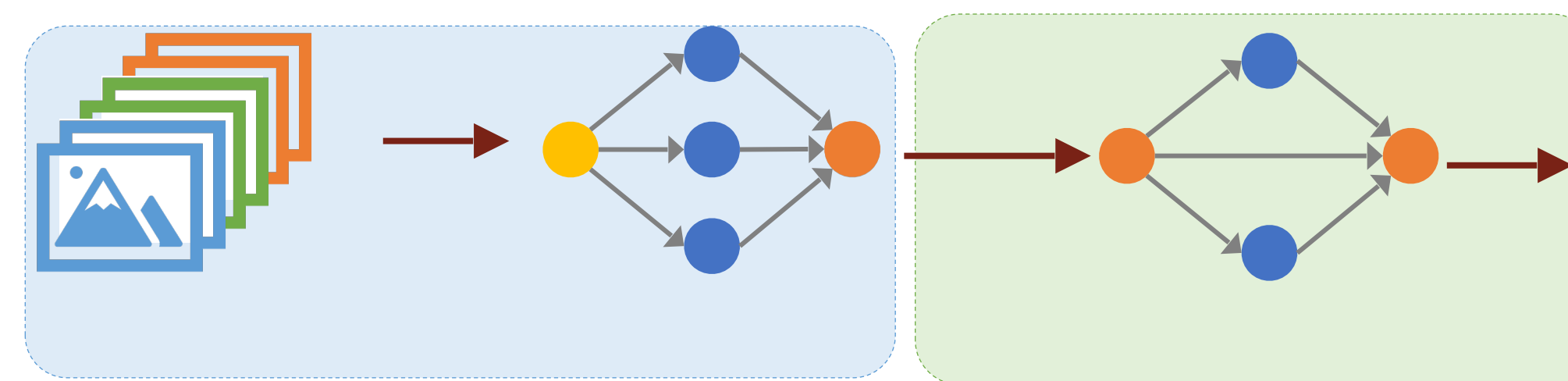
- Data Parallelism
- Model Parallelism
- **Compare the Advantages and Disadvantages of Two Parallelism**

Comparison between two parallelism



Data Parallelism:

- Split the data
- Same model across devices
- Easy to parallelize, high utilization
- N copies of model



Model Parallelism:

- Split the model
- Move activations through devices
- Hard to parallelize, load balancing issue
- Single copy of model

Figures credit from CMU 15-849 [Jia 2022]



Alpa Automating Inter- and Intra-Operator Parallelism for Distributed Deep Learning

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Eric P. Xing⁵ Joseph E. Gonzalez¹ Ion Stoica¹

¹UC Berkeley **²Amazon Web Services** **³Google** **⁴Shanghai Jiao Tong University**
⁵MBZUAI & Carnegie Mellon University **⁶Duke University**

*Equal contribution

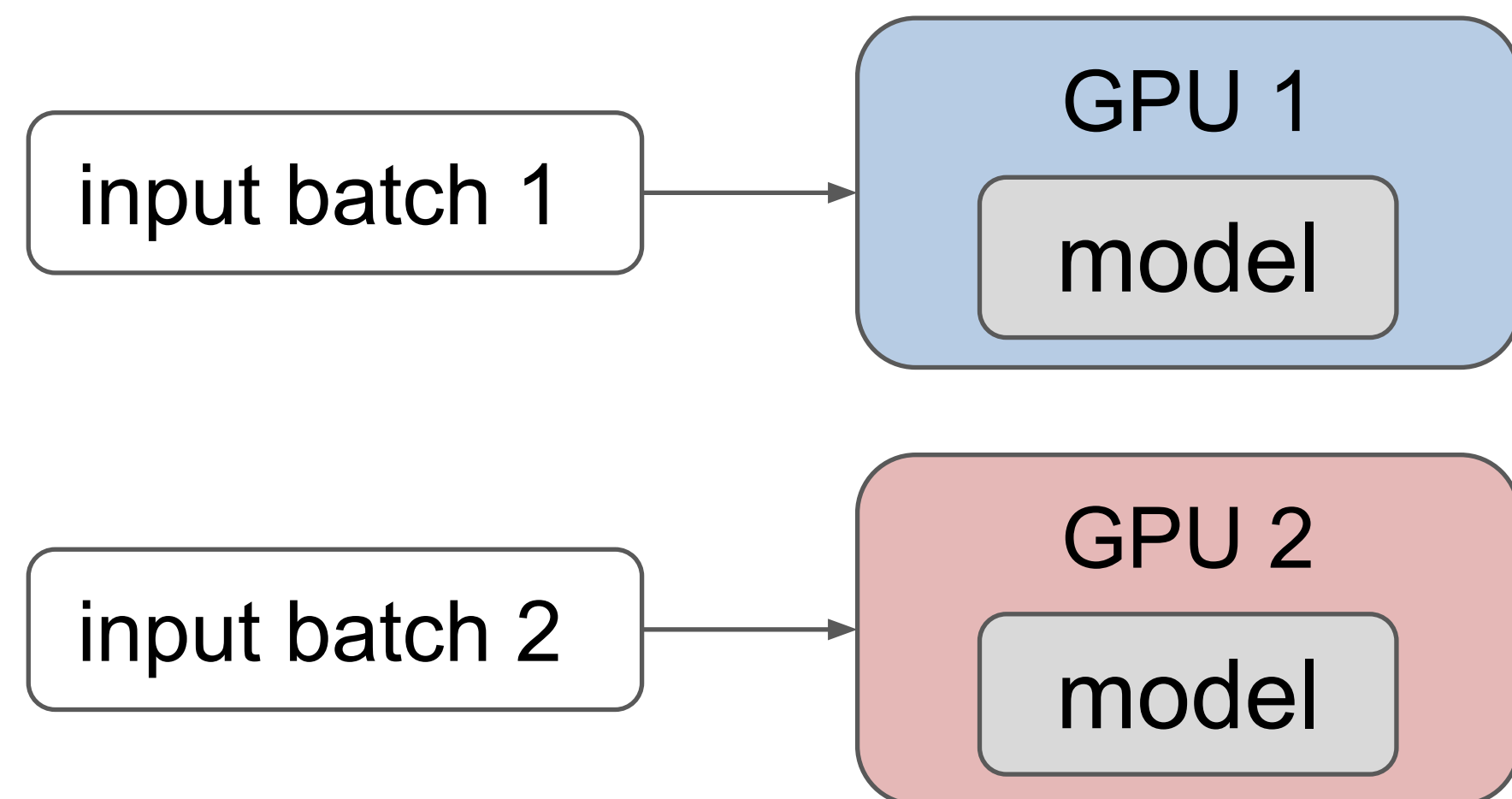


What are System Challenges?

1. What if the input dataset is very large?

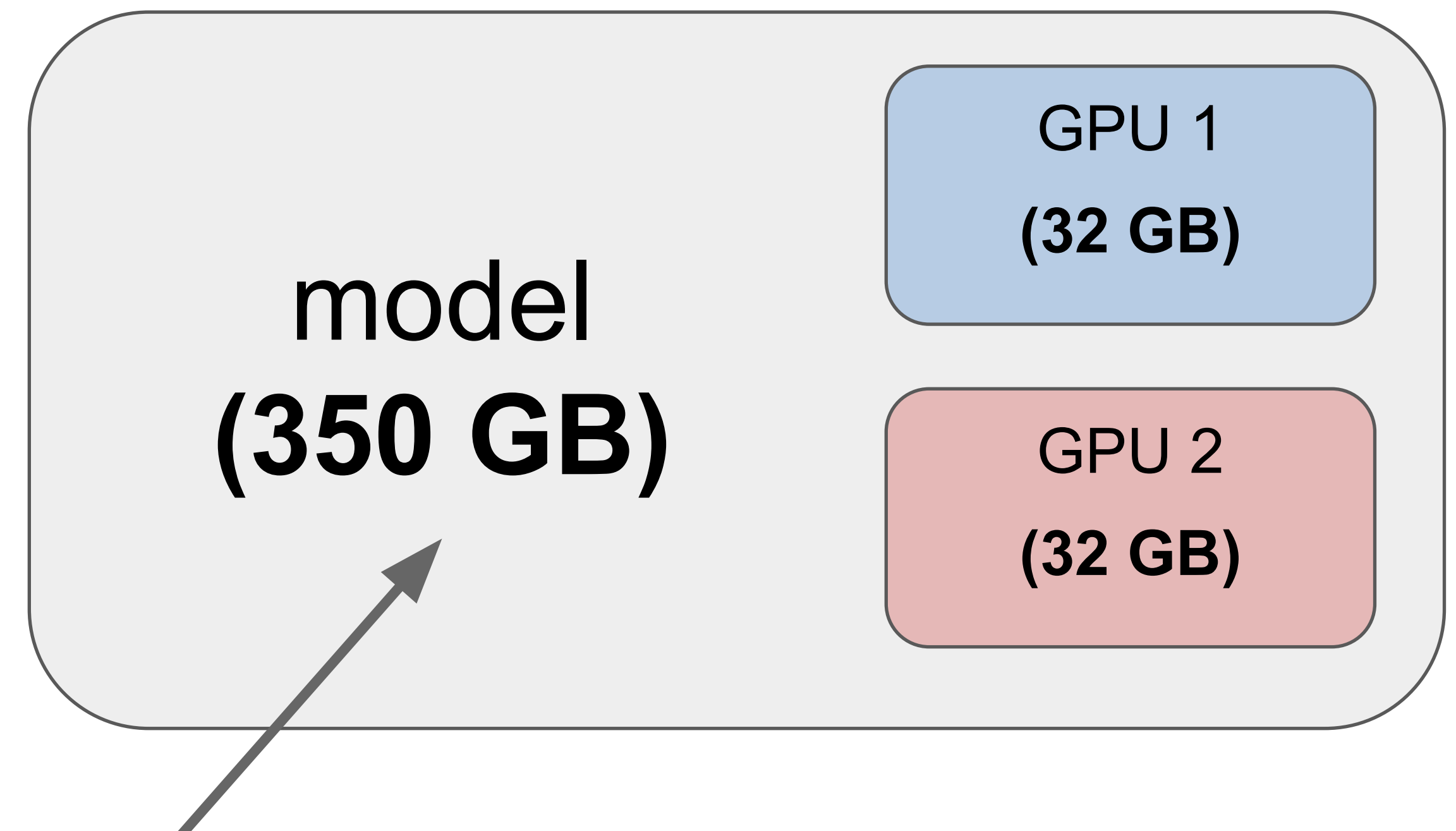
😊 **Easy.**

Use data parallelism: partition input data and replicate the model



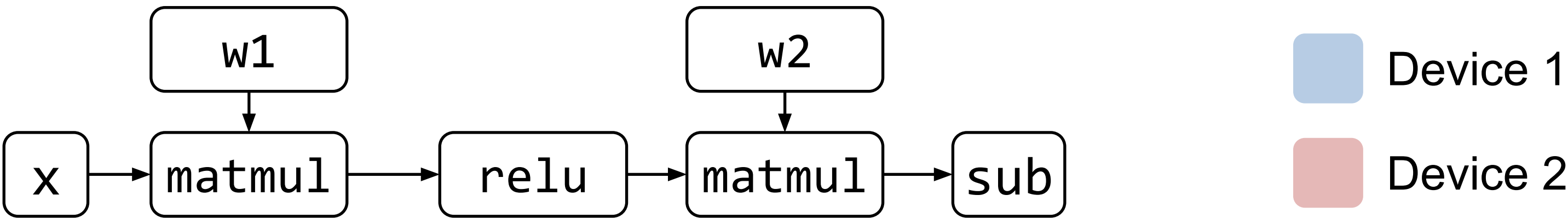
2. What if the model is very large?

😞 **Hard !!**



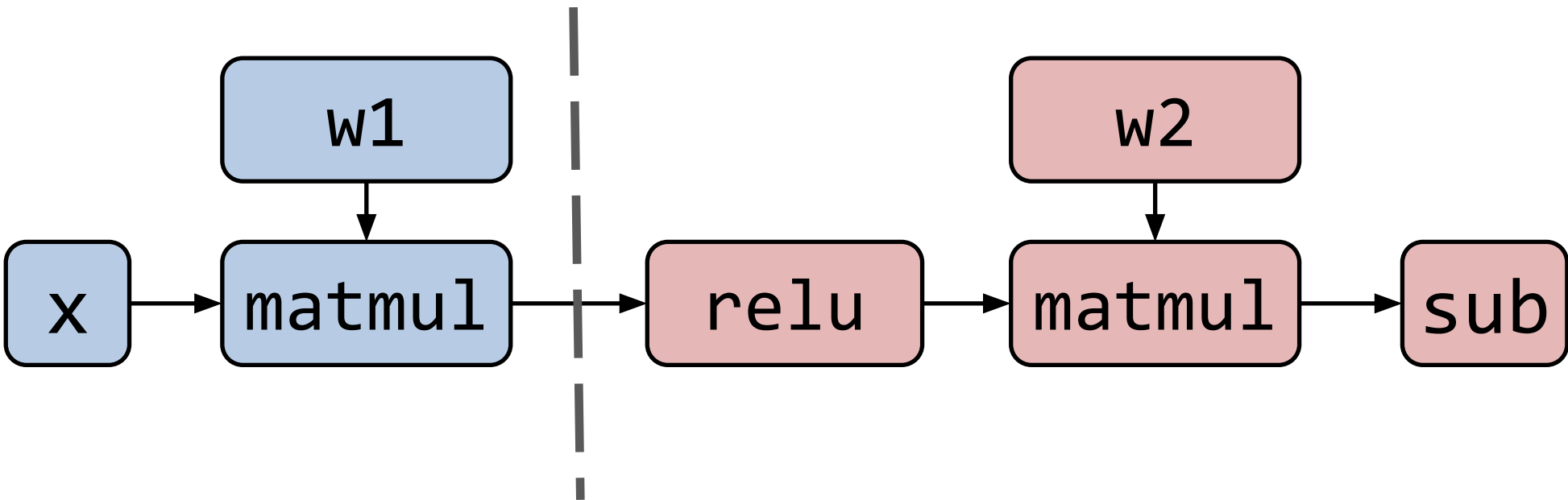
Challenge: How to partition a computational graph?

Partition Computational Graphs



Device 1
Device 2

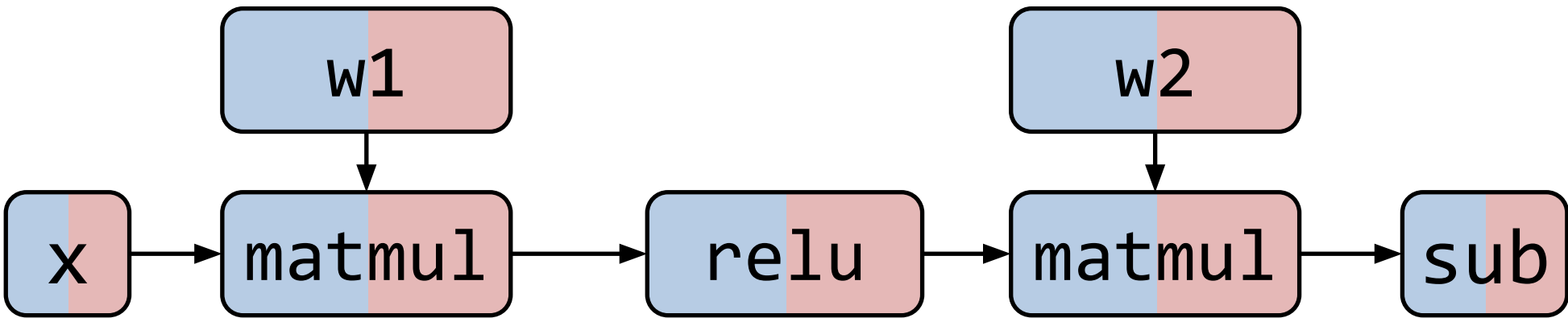
Strategy 1: Inter-operator Parallelism



Trade-off

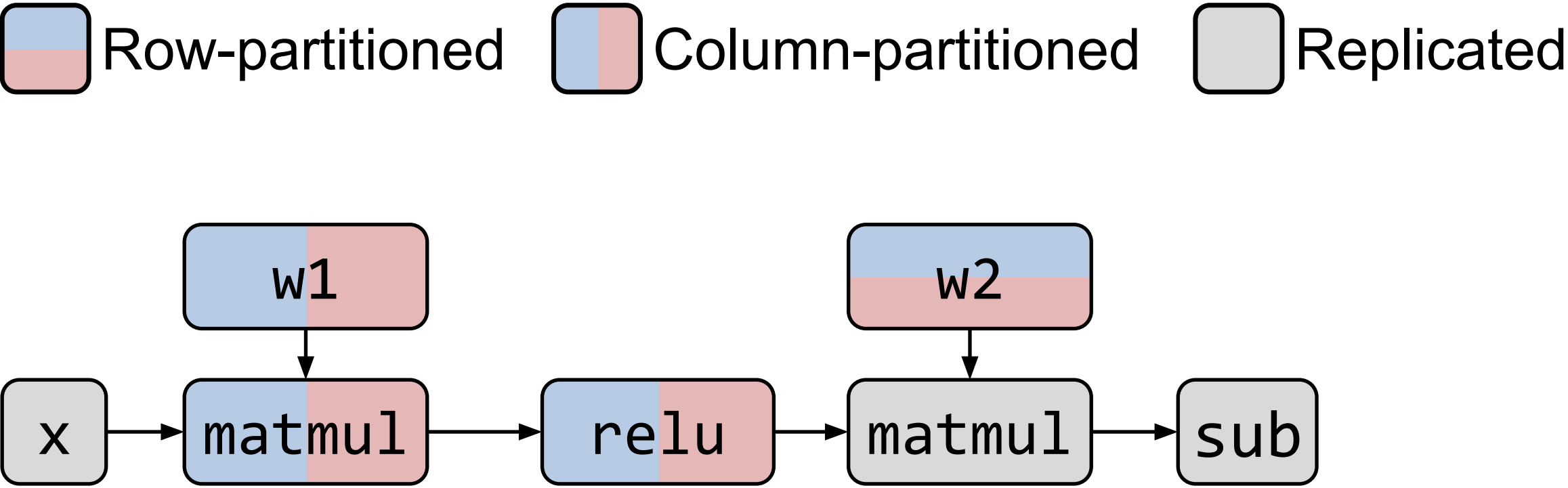
	Inter-operator Parallelism	Intra-operator Parallelism
Communication	Less	More
Device Idle Time	More	Less

Strategy 2: Intra-operator Parallelism

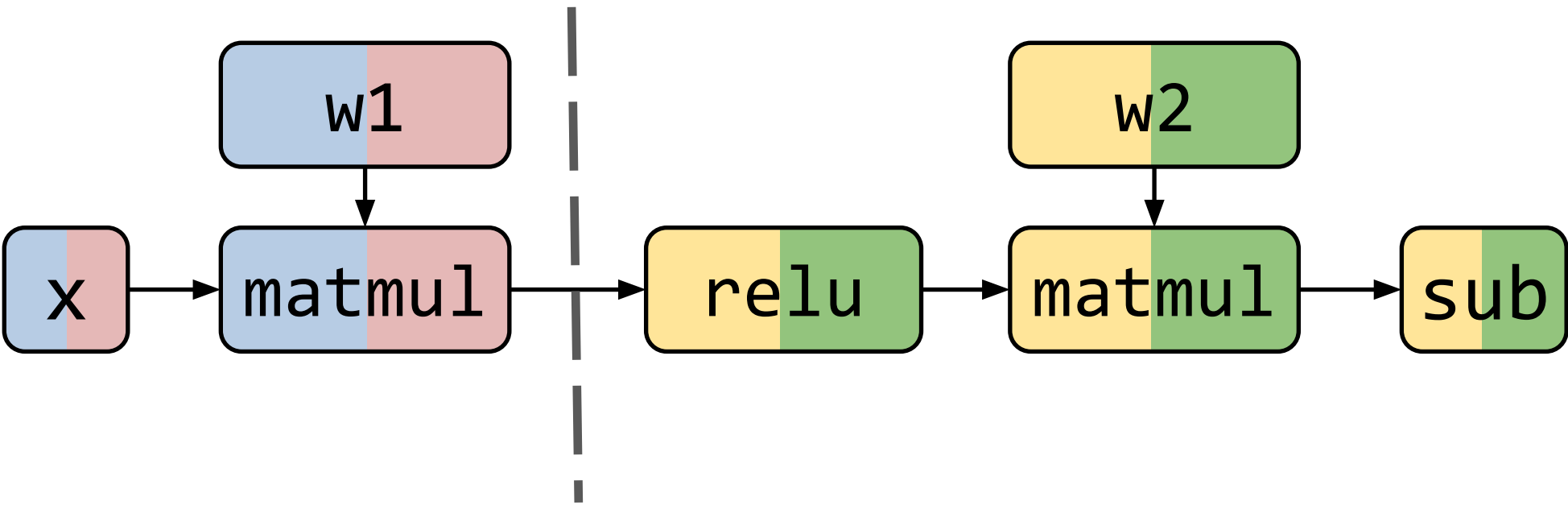


Partition Computational Graphs

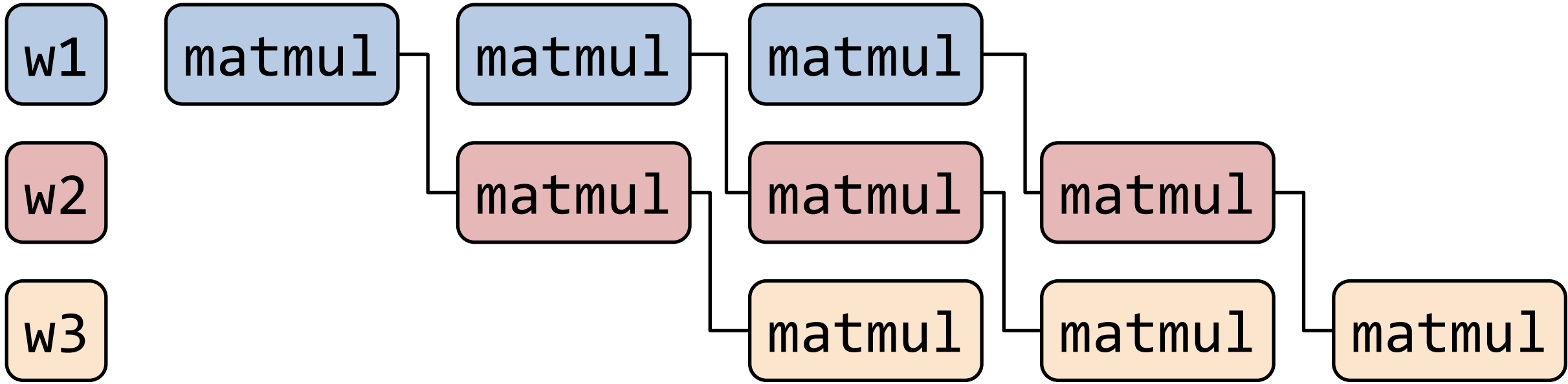
Multiple intra-op strategies for a single node



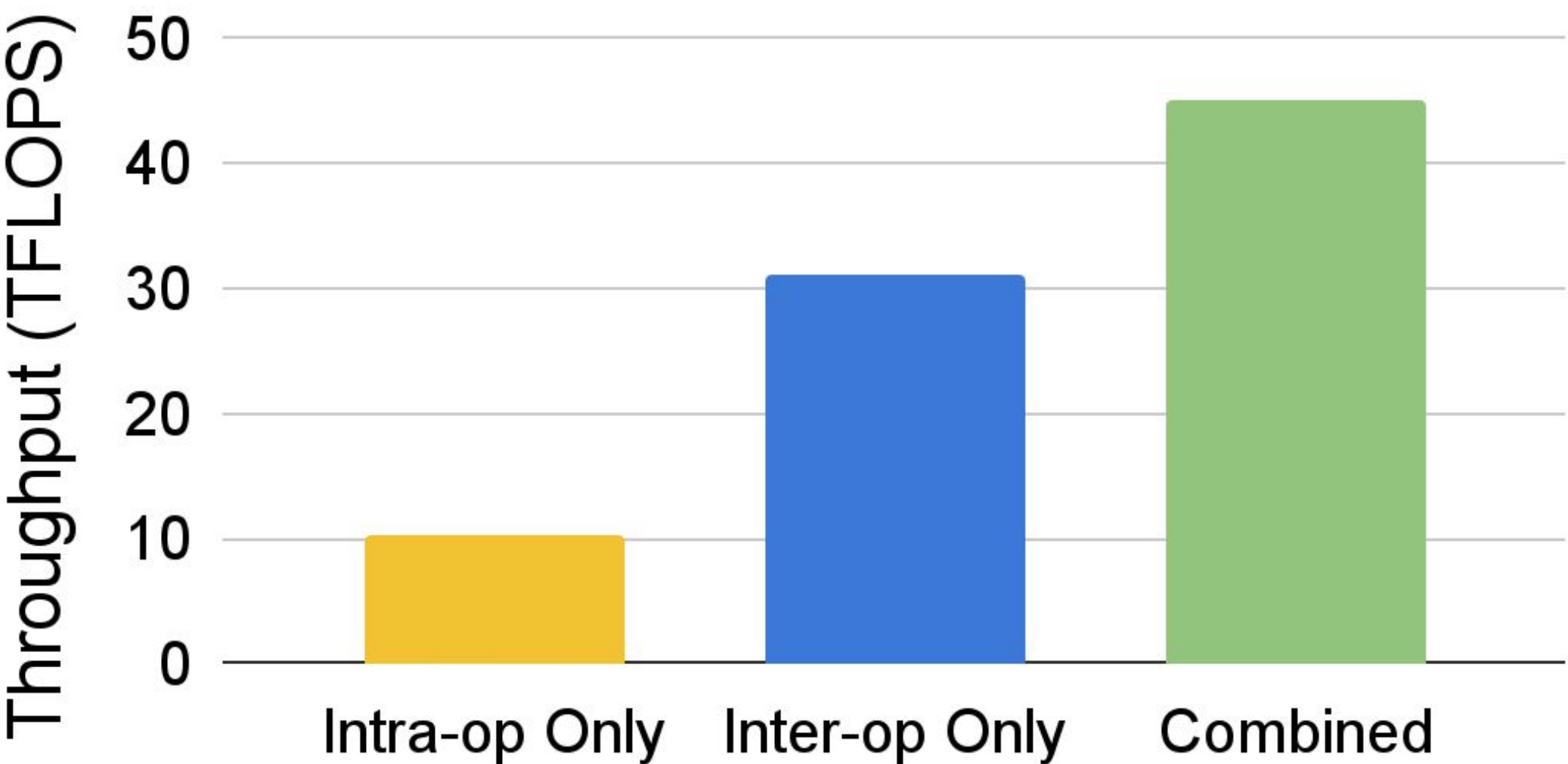
Combine Intra-op and Inter-op



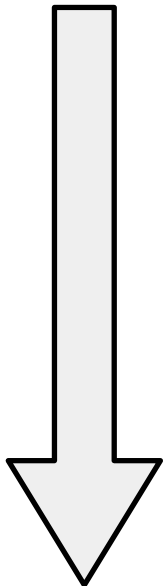
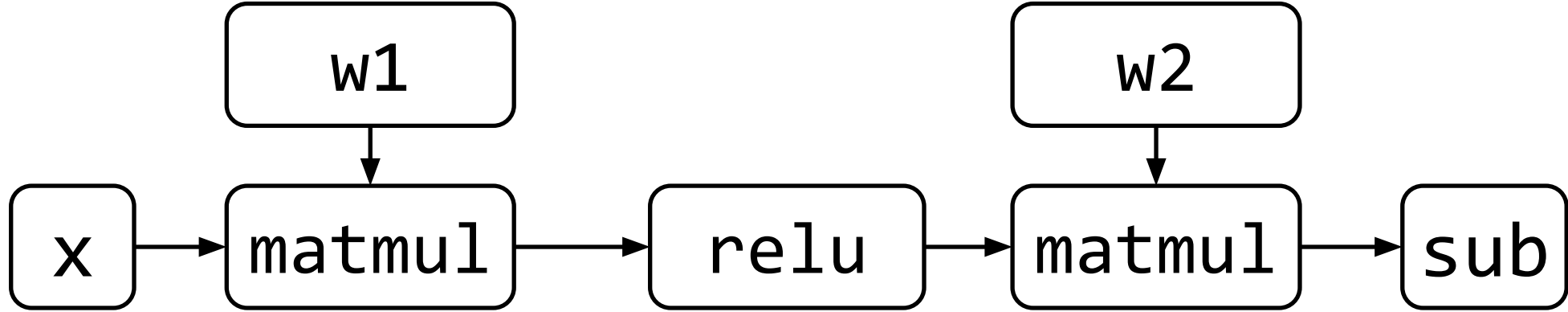
Pipeline the execution for inter-op parallelism



Training Throughput of an MoE Model



Network Topology



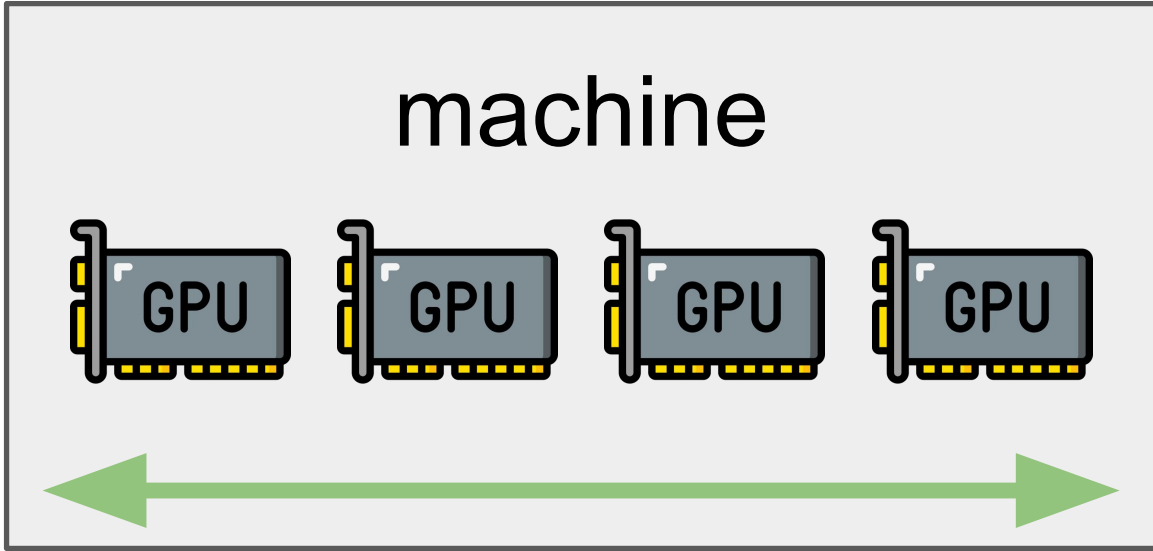
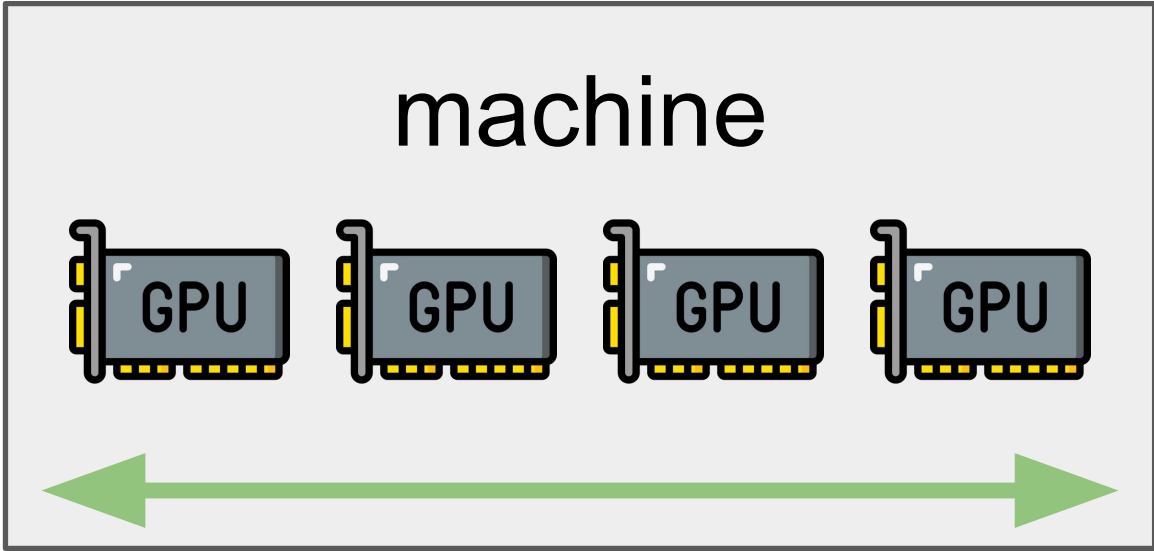
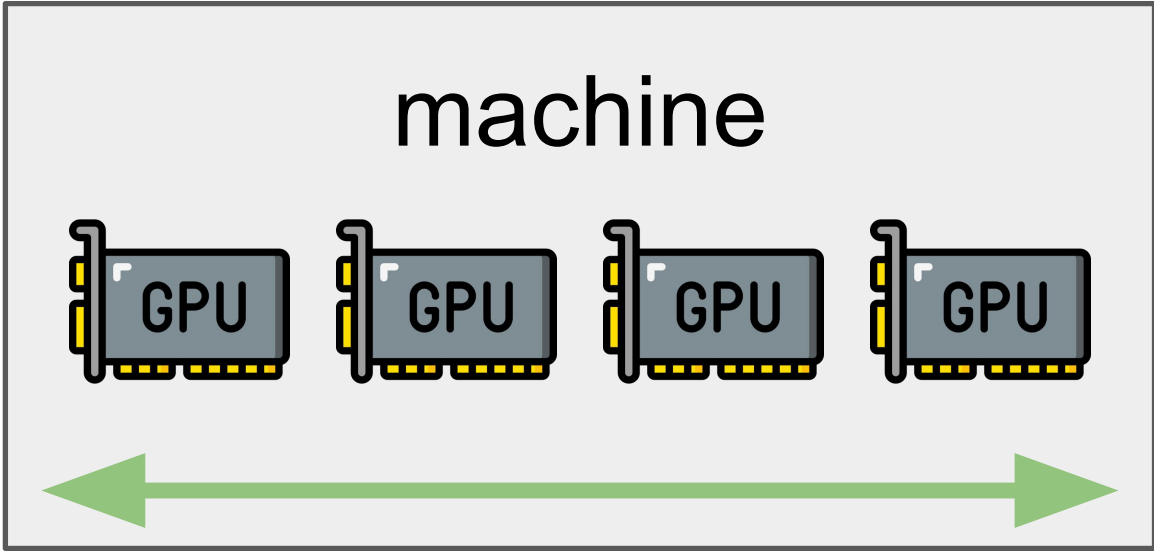
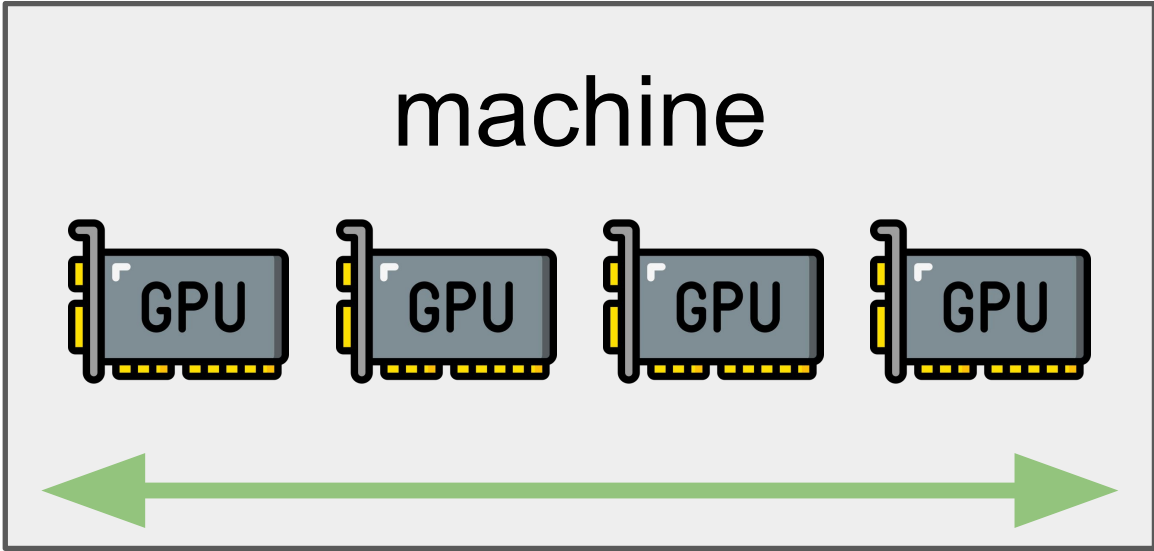
Challenge: How to handle heterogeneous network topology?



Fast connections



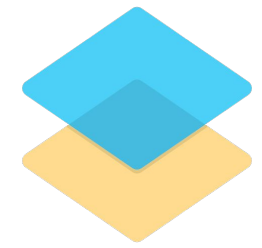
Slow connections





A unified **compiler** that **automatically** finds and executes the best **Inter-op** and **Intra-op** parallelism for **large** deep learning models.

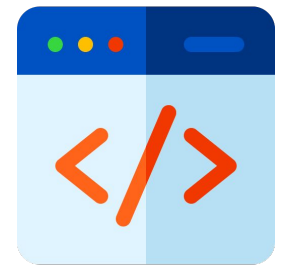
Alpa's Main Contributions



Two-level hierarchical space of parallelism techniques.

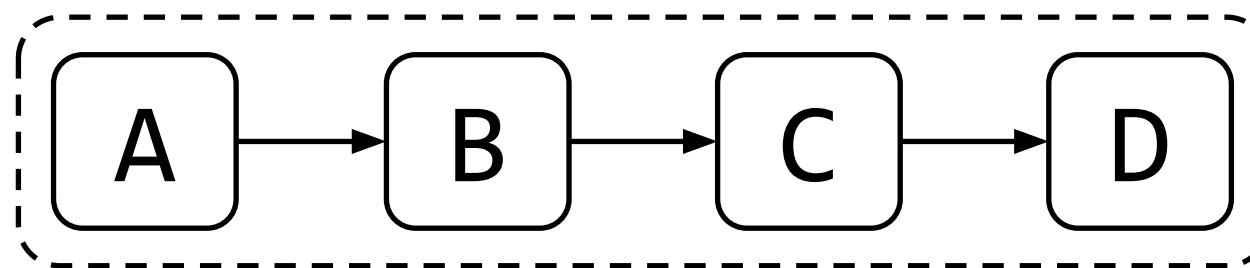


Effective optimization algorithms at each level.

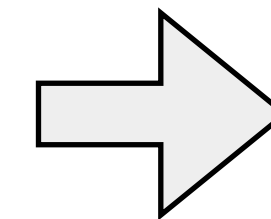
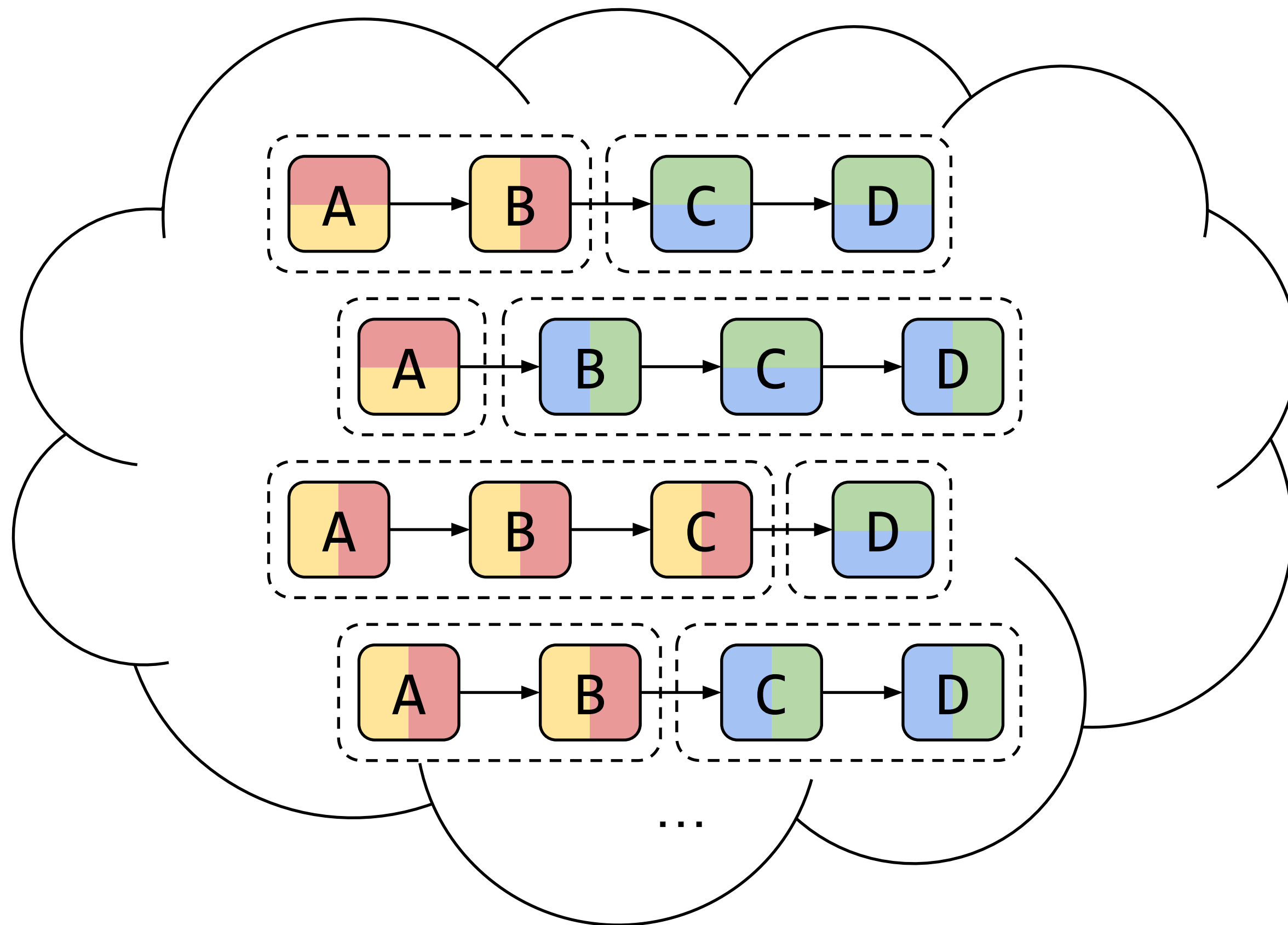


Efficient compiler and runtime system implementation.

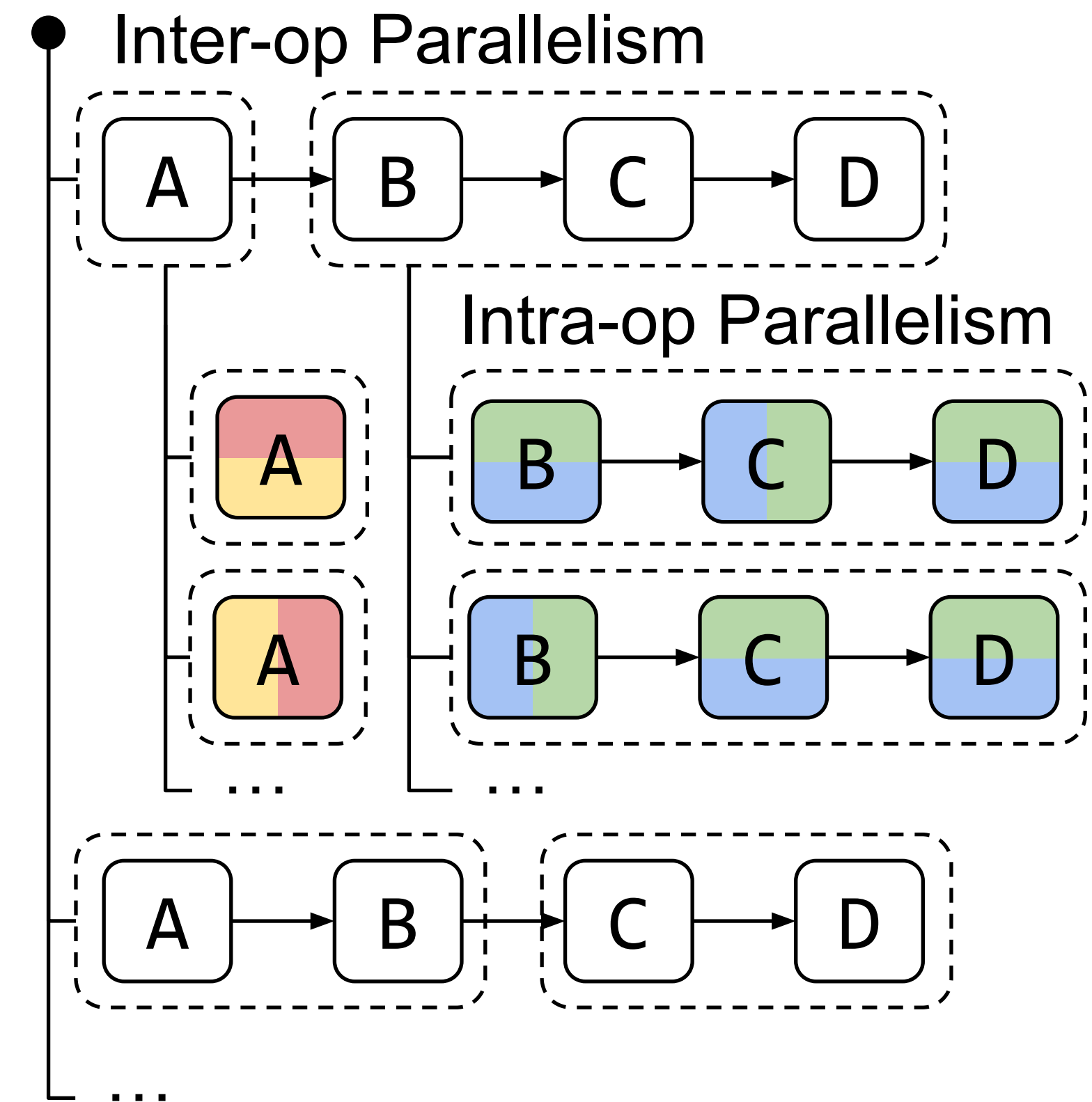
Computational Graph



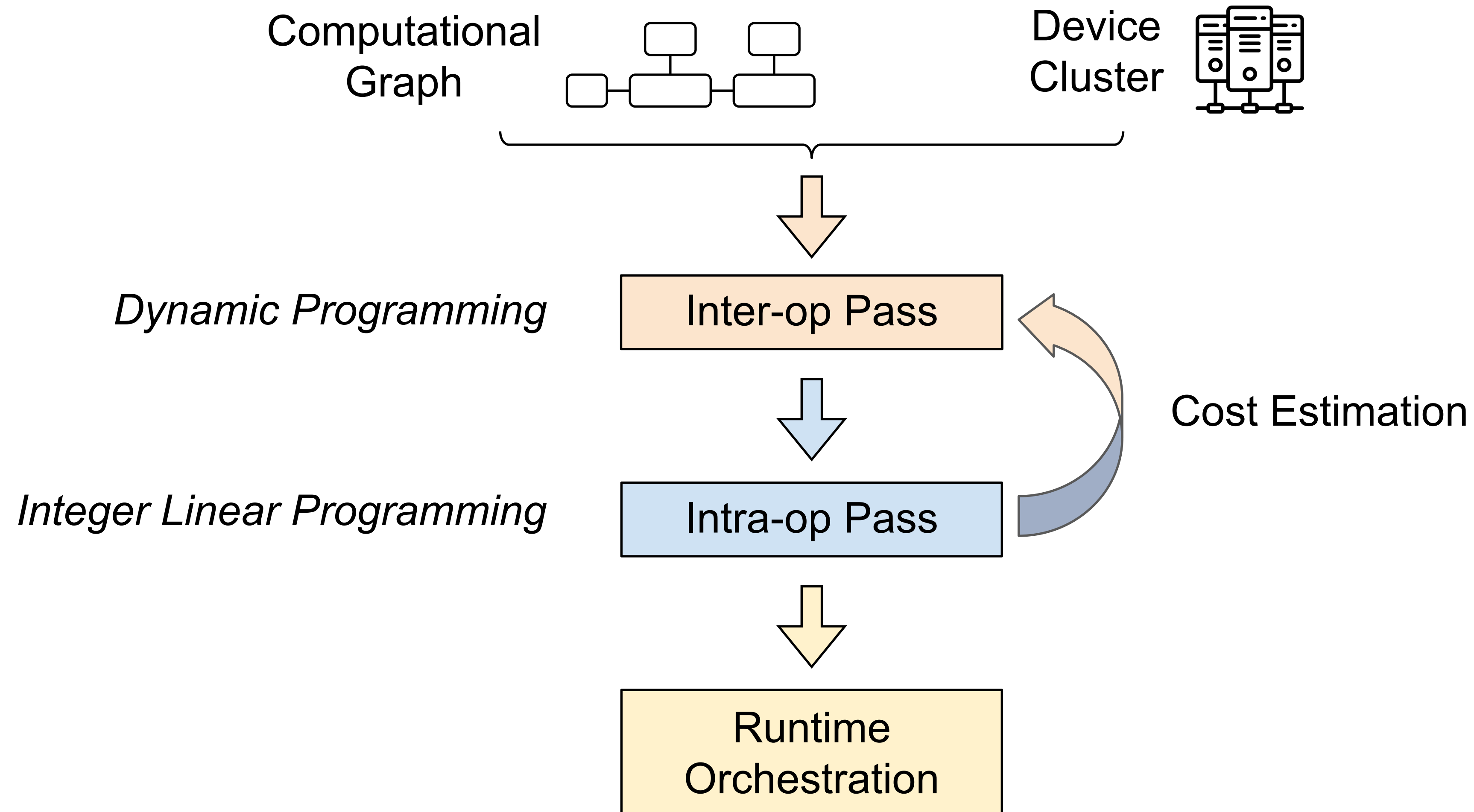
Whole Search Space



Alpha Hierarchical Space

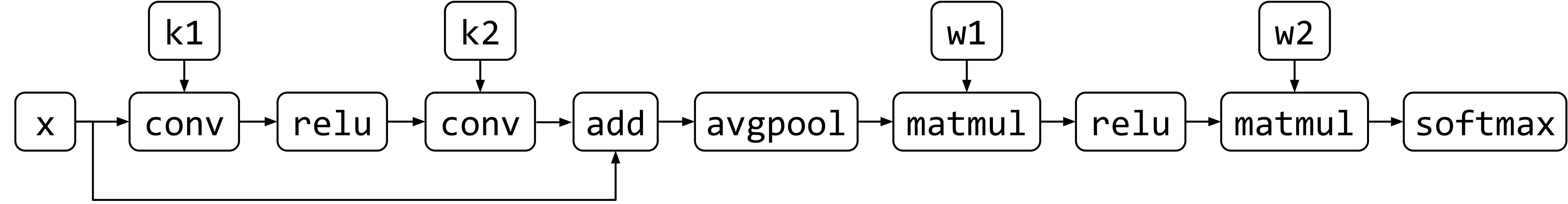


Alpa Compiler: Hierarchical Optimization



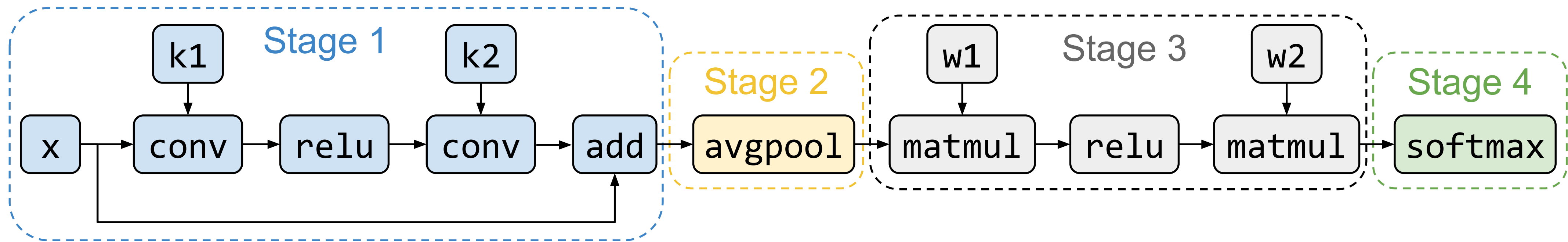
Inter-op Pass

Computational Graph

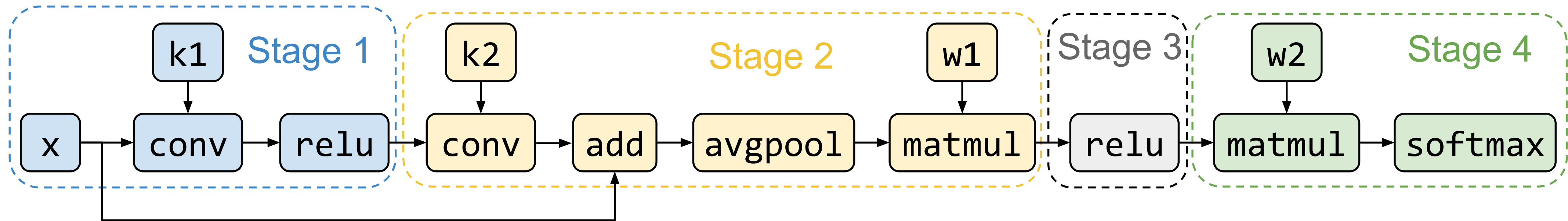


Inter-op Pass

Graph Partitioning



or

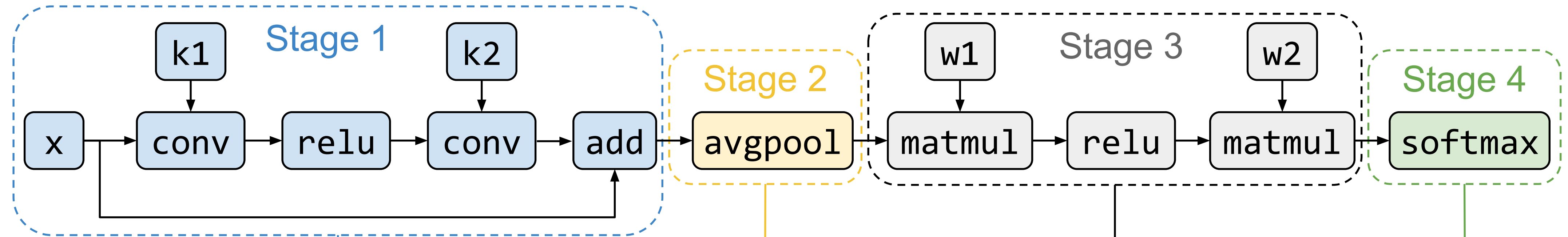


or

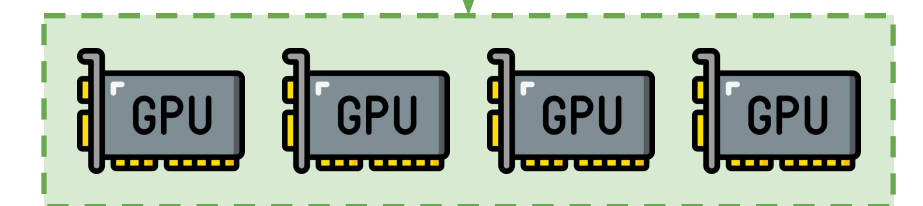
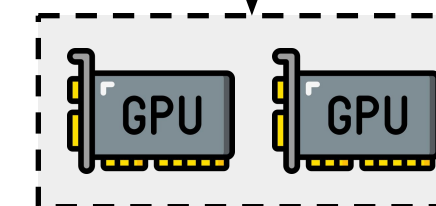
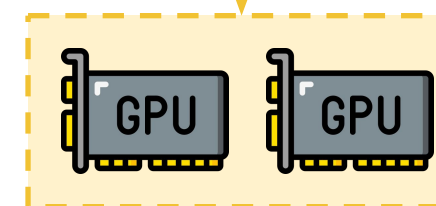
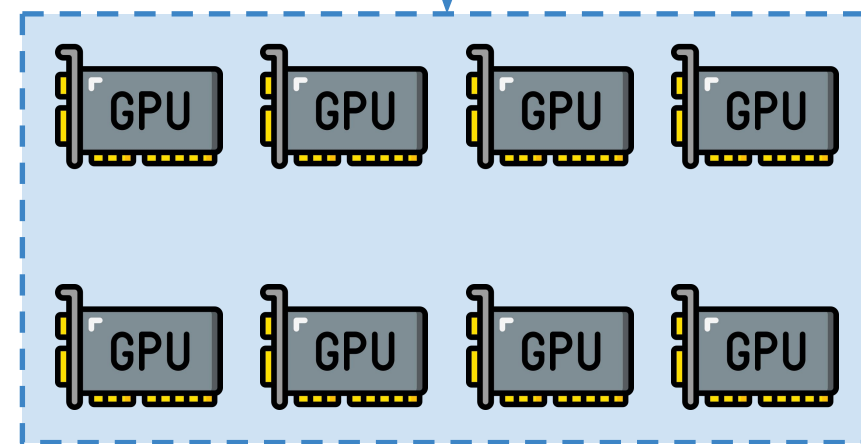
...

Inter-op Pass

Partitioned Computational Graph

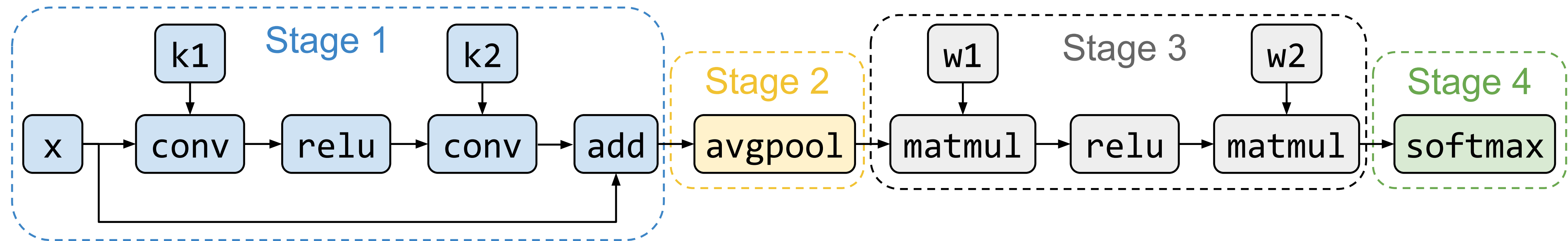


Device Assignment



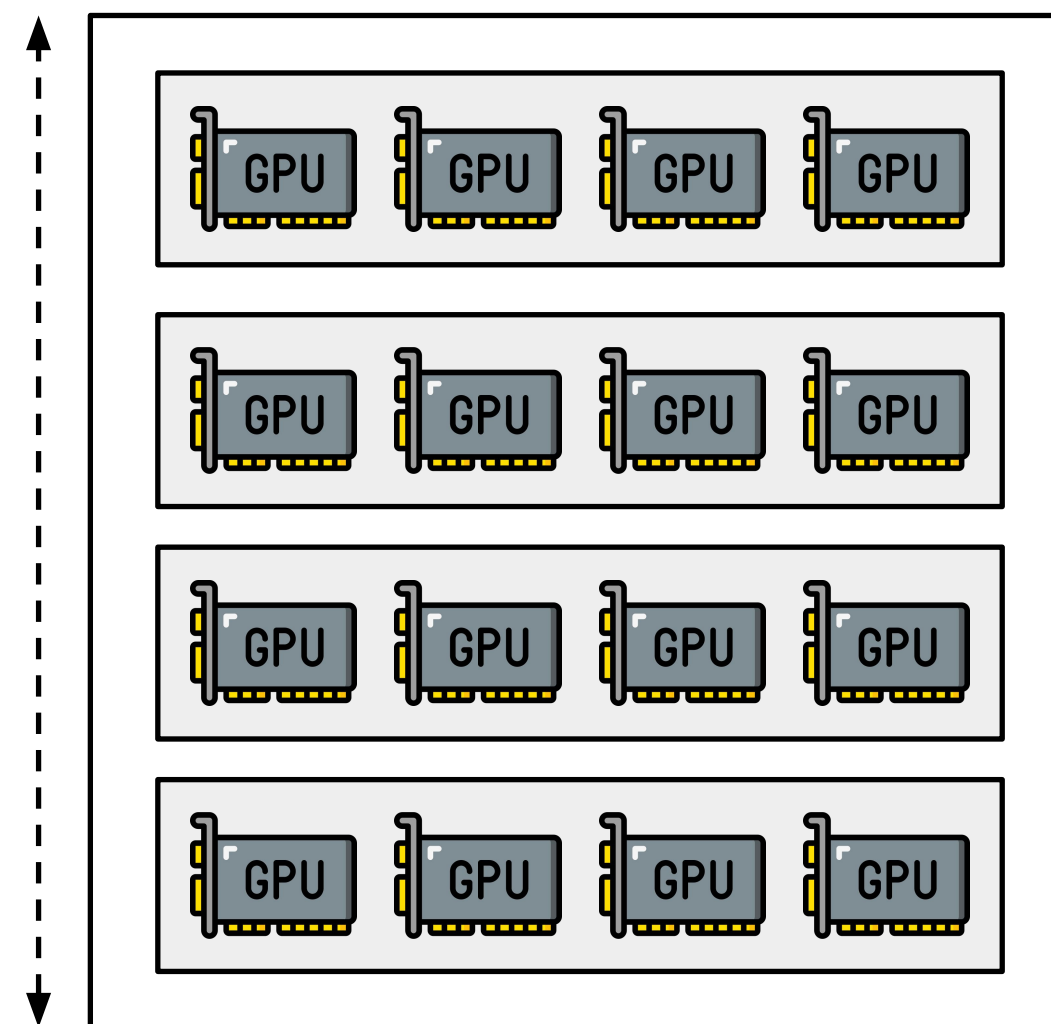
Inter-op Pass

Partitioned Computational Graph



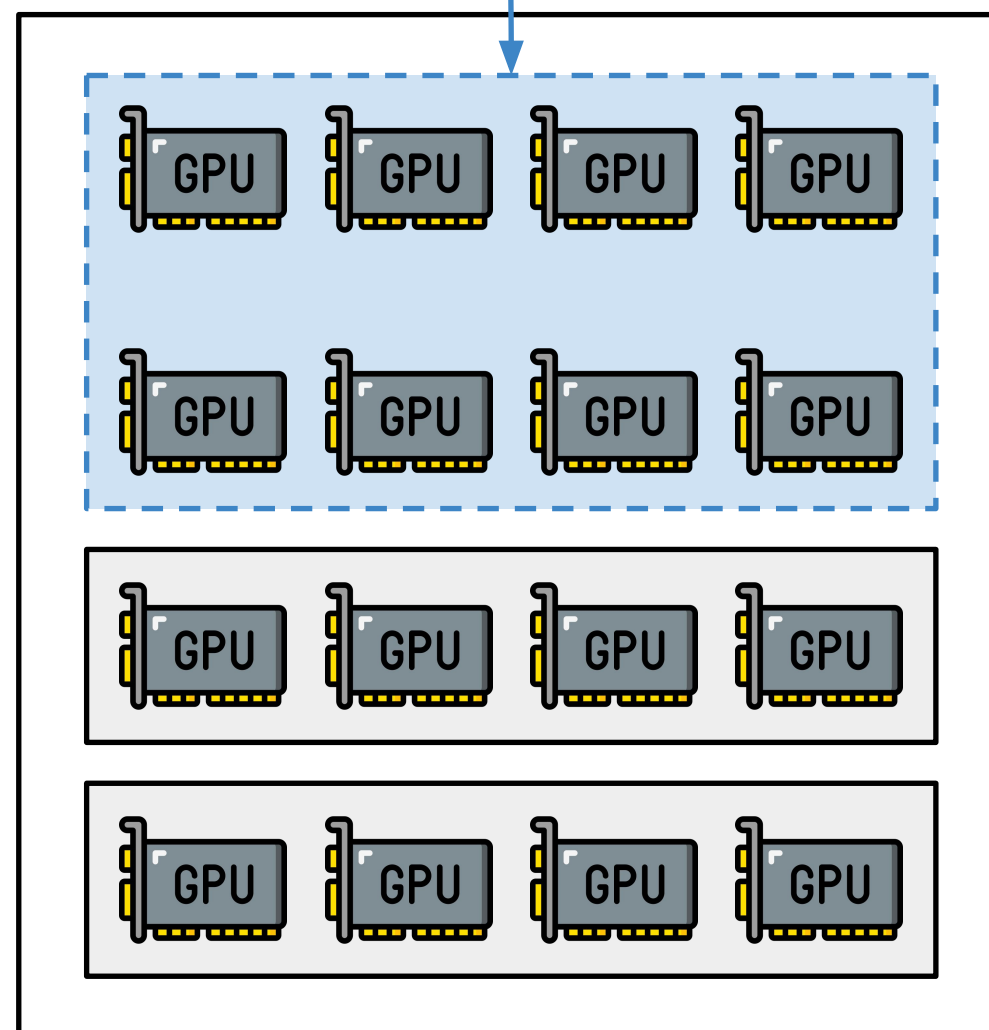
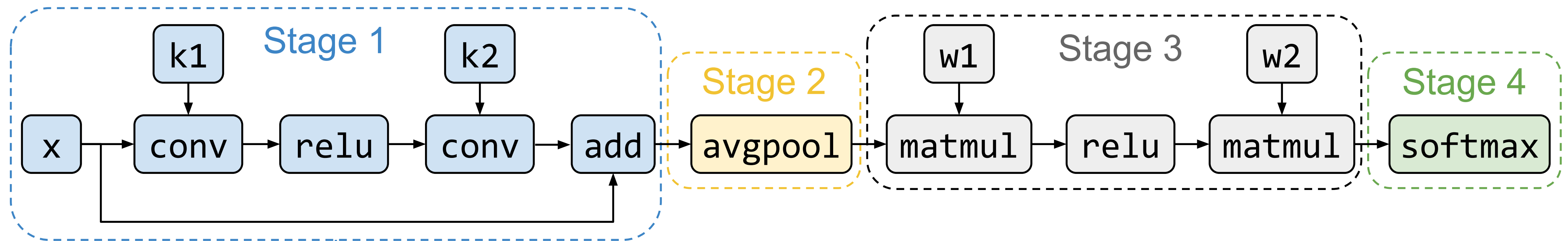
Cluster (2D Device Mesh)

Nodes 🐢



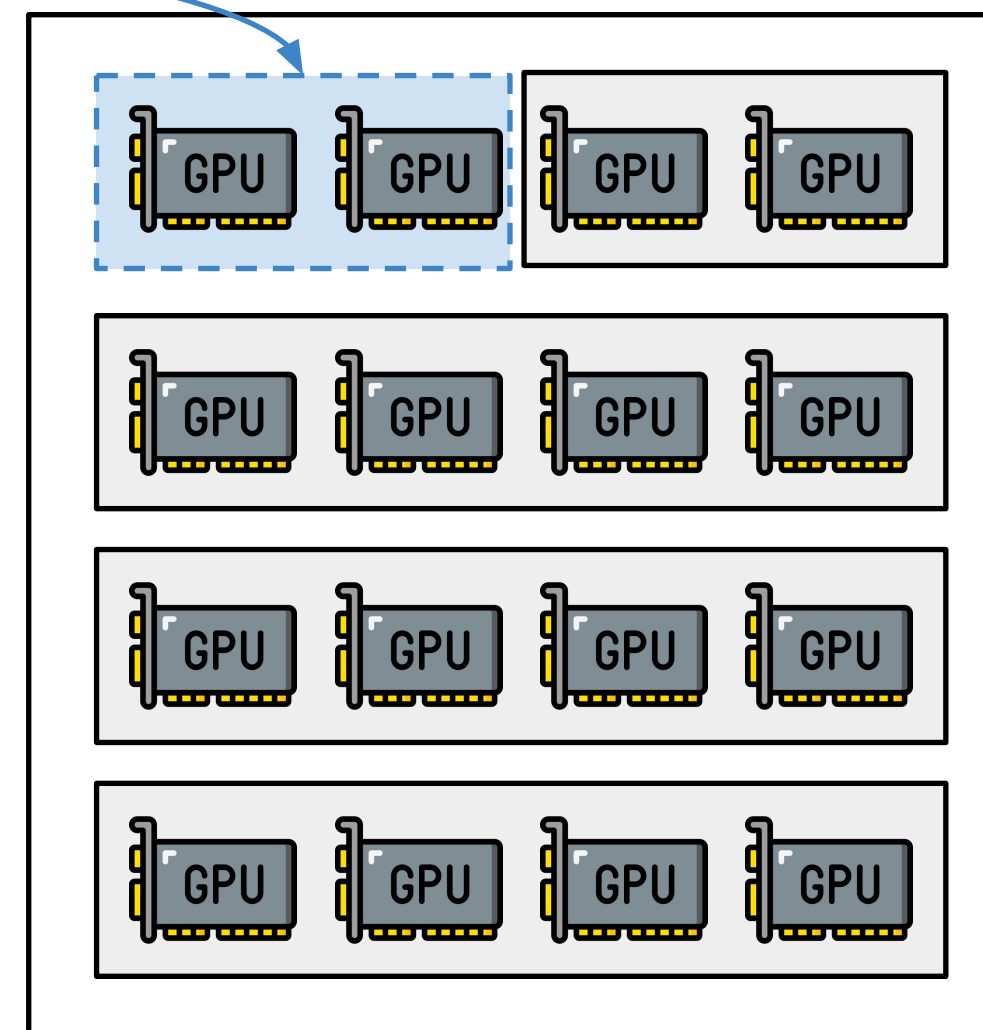
GPUs within a Node 🐰

Inter-op Pass



Submesh Choice 1

or

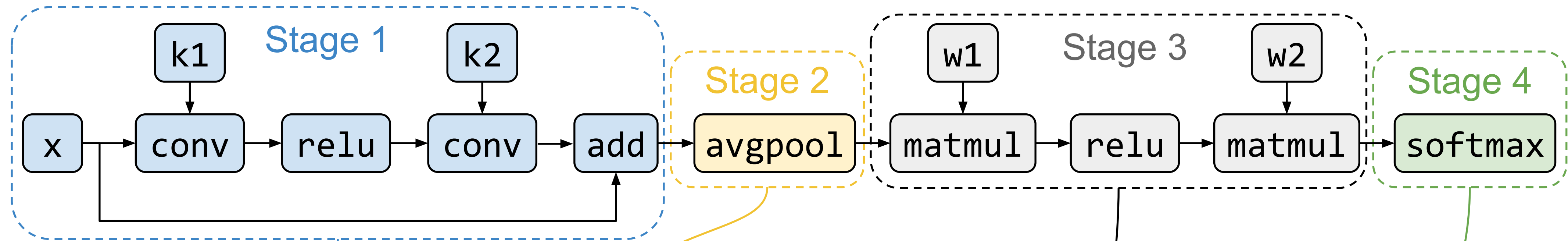


Submesh Choice 2

or

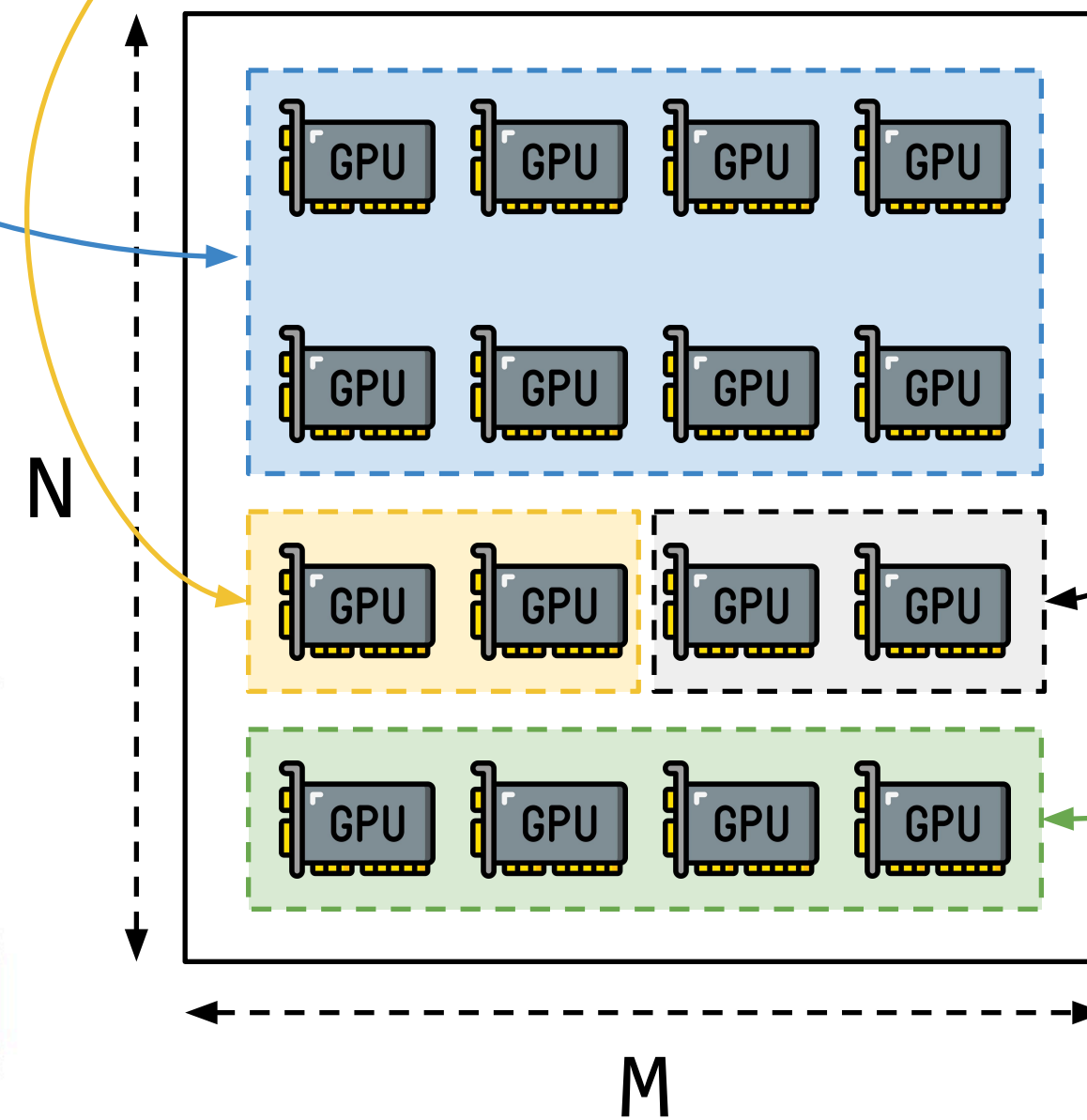
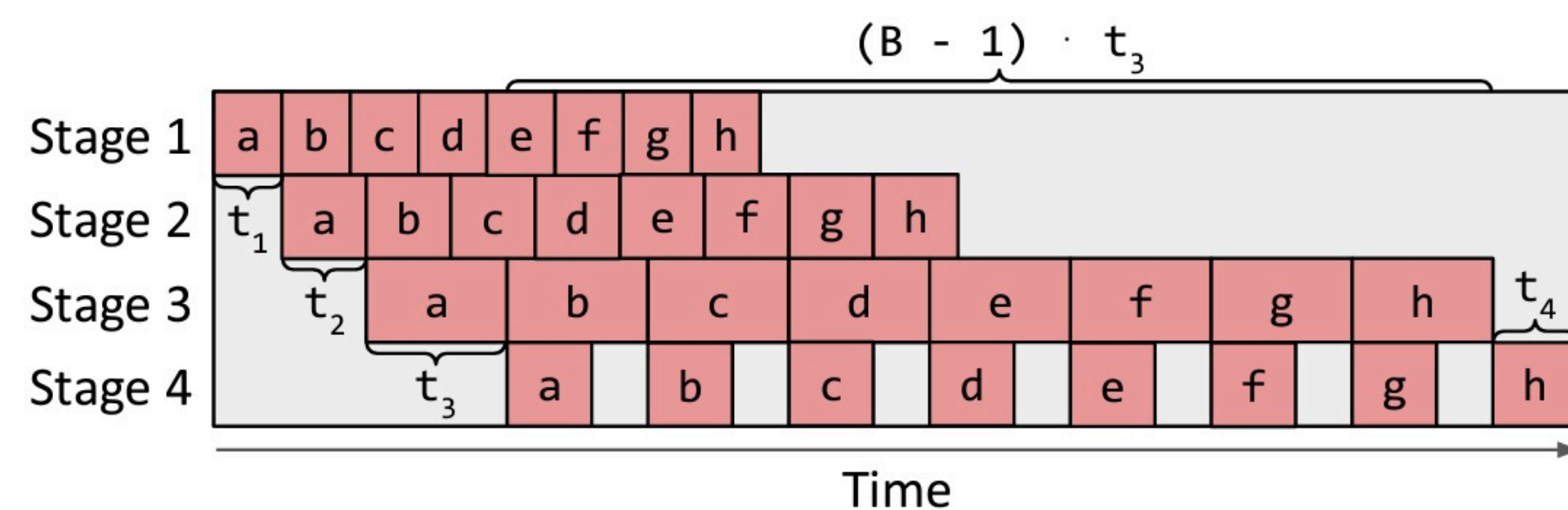
...

Inter-op Pass



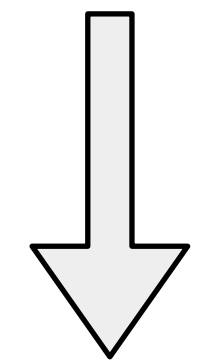
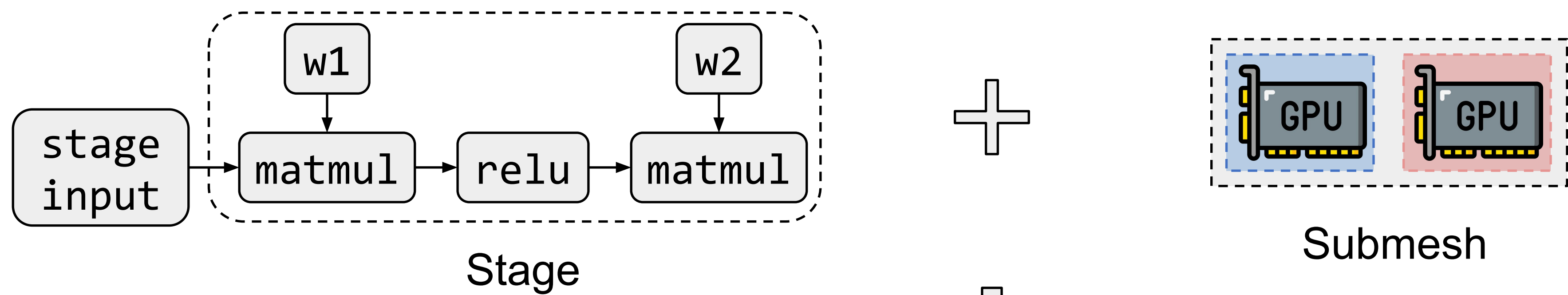
$$T^* = \min_{\substack{s_1, \dots, s_S; \\ (n_1, m_1), \dots, (n_S, m_S)}} \left\{ \sum_{i=1}^S t_i + (B-1) \cdot \max_{1 \leq j \leq S} \{t_j\} \right\}.$$

Solved together by
Dynamic Programming

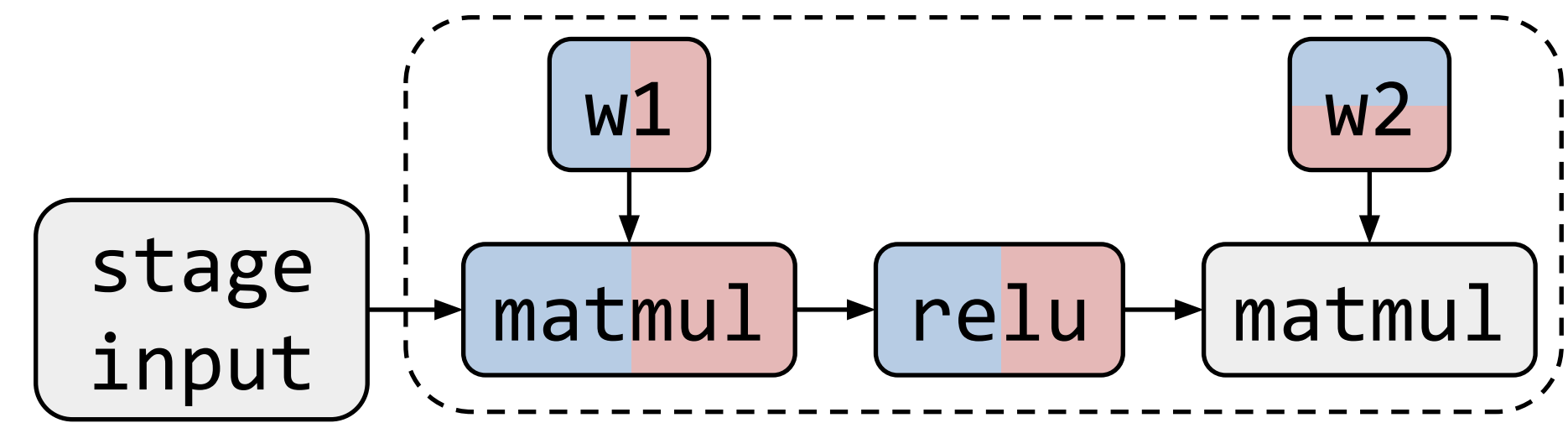


More details on the
DP algorithm can be
found in the paper.

Intra-op Pass



Solved by
**Integer Linear
Programming**



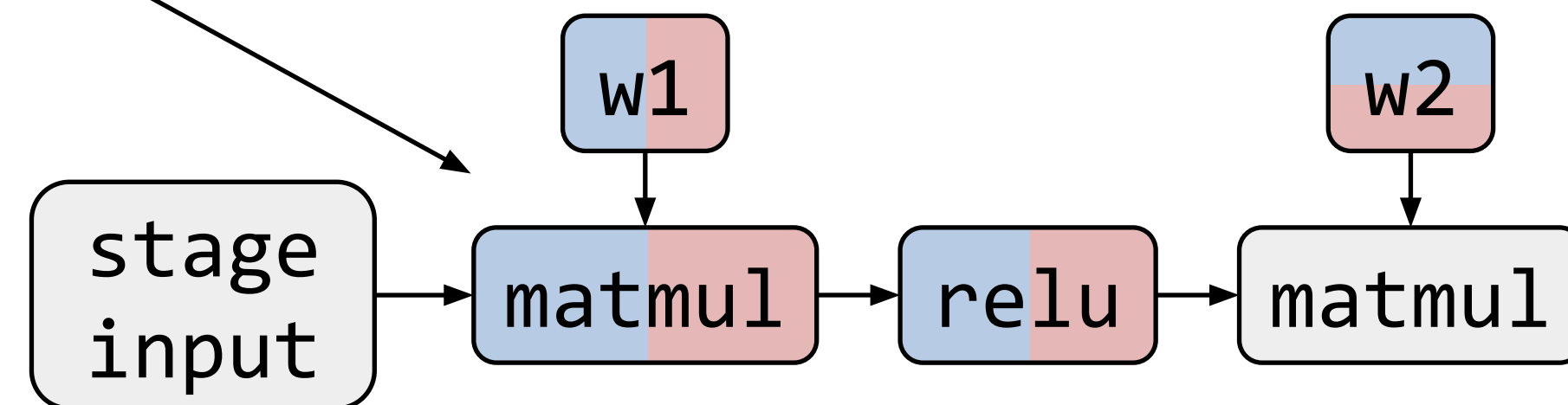
Stage with intra-operator
parallelization

Intra-op Pass

Integer Linear Programming Formulation

Decision vector

Parallel strategies of each operator



Minimize Computation cost + Communication cost

More details on the ILP algorithm can be found in the paper.

Compilation Time Optimization

Communication-aware
operator clustering in
ILP & DP

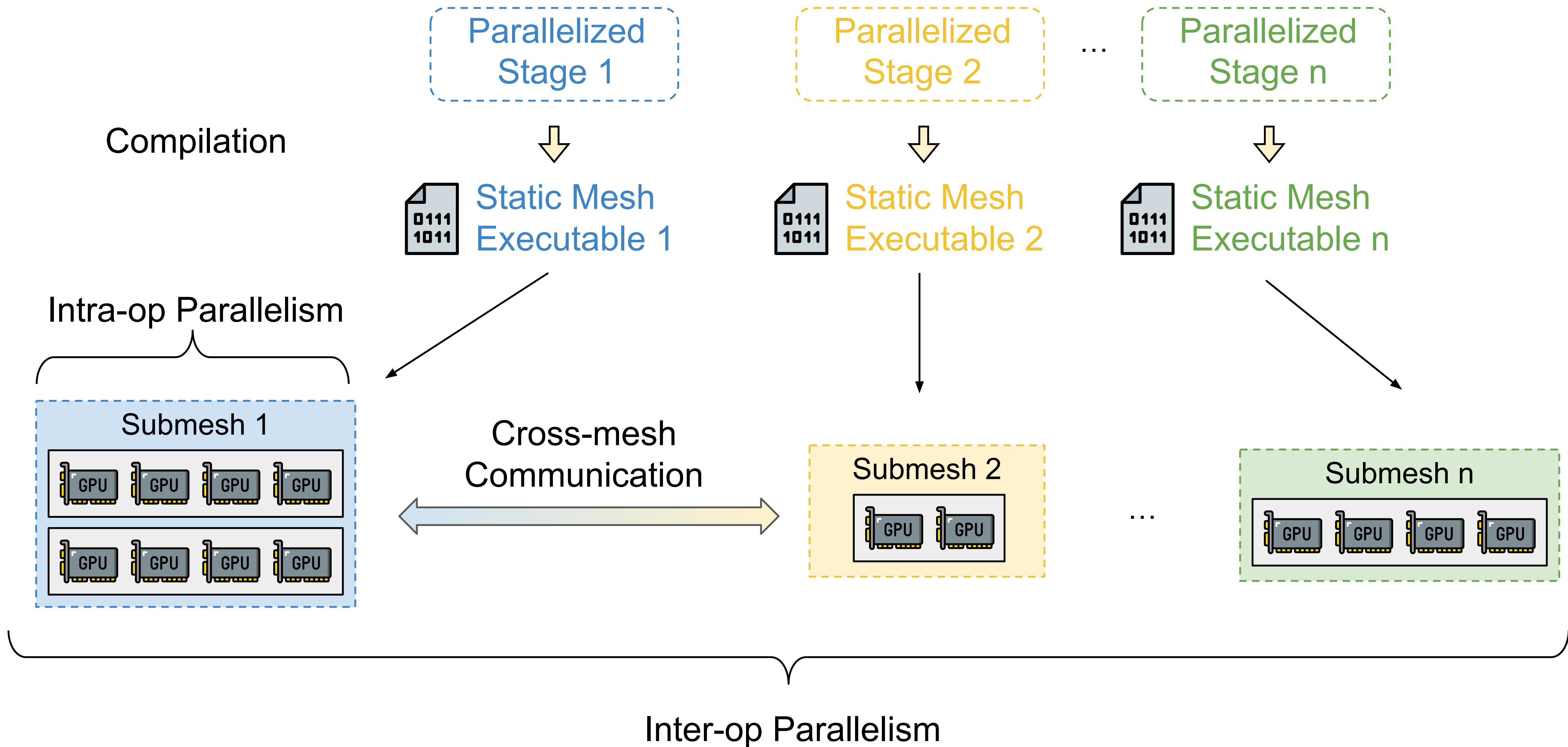
Early stopping in DP

Distributed
Compilation

Alpa Compilation Time: < 40 min for the largest experiment.

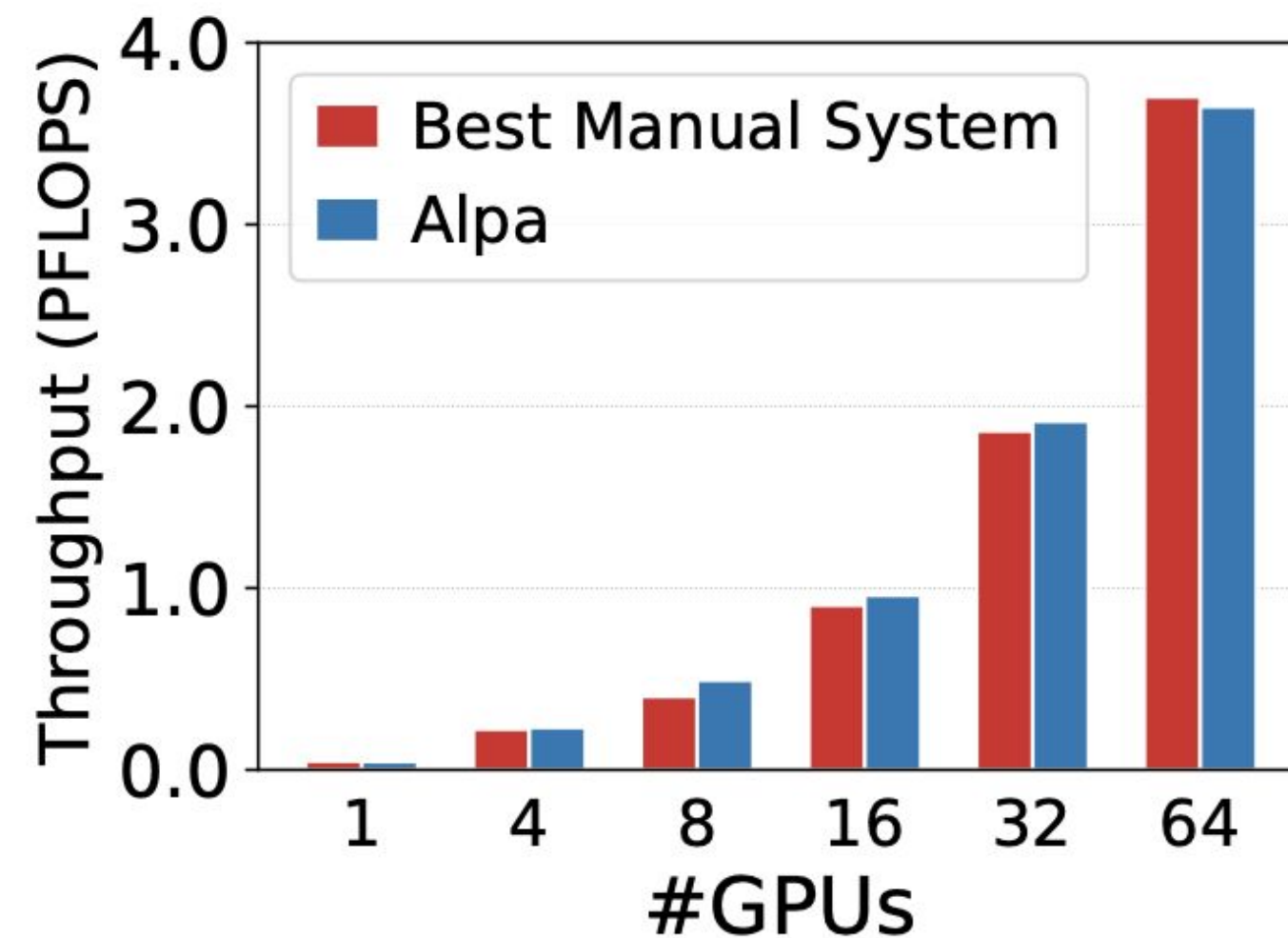
- Can be further reduced by at least 50% with search space pruning.

Runtime Orchestration



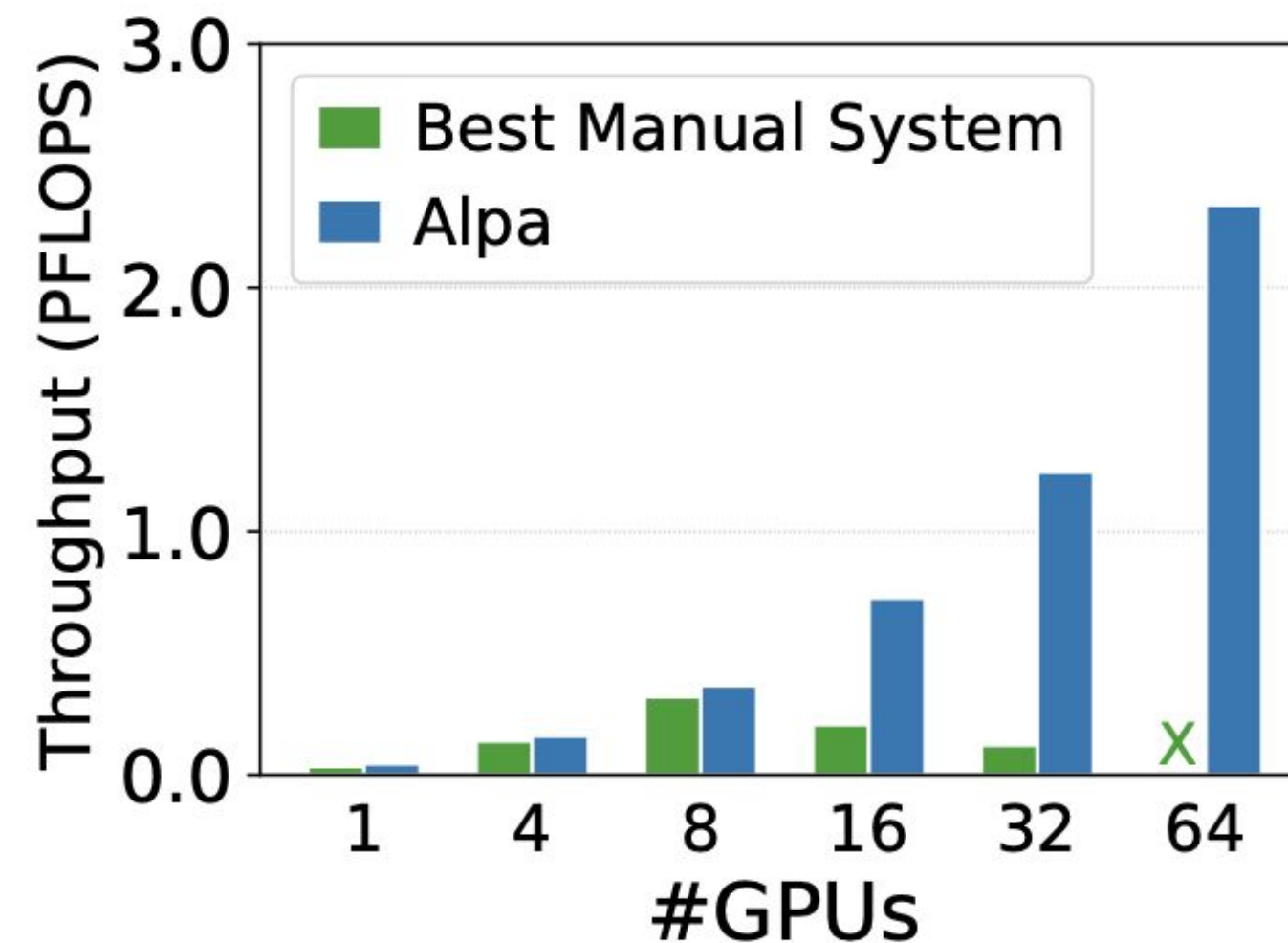
Evaluation: Comparing with Previous Works

GPT (up to 39B)



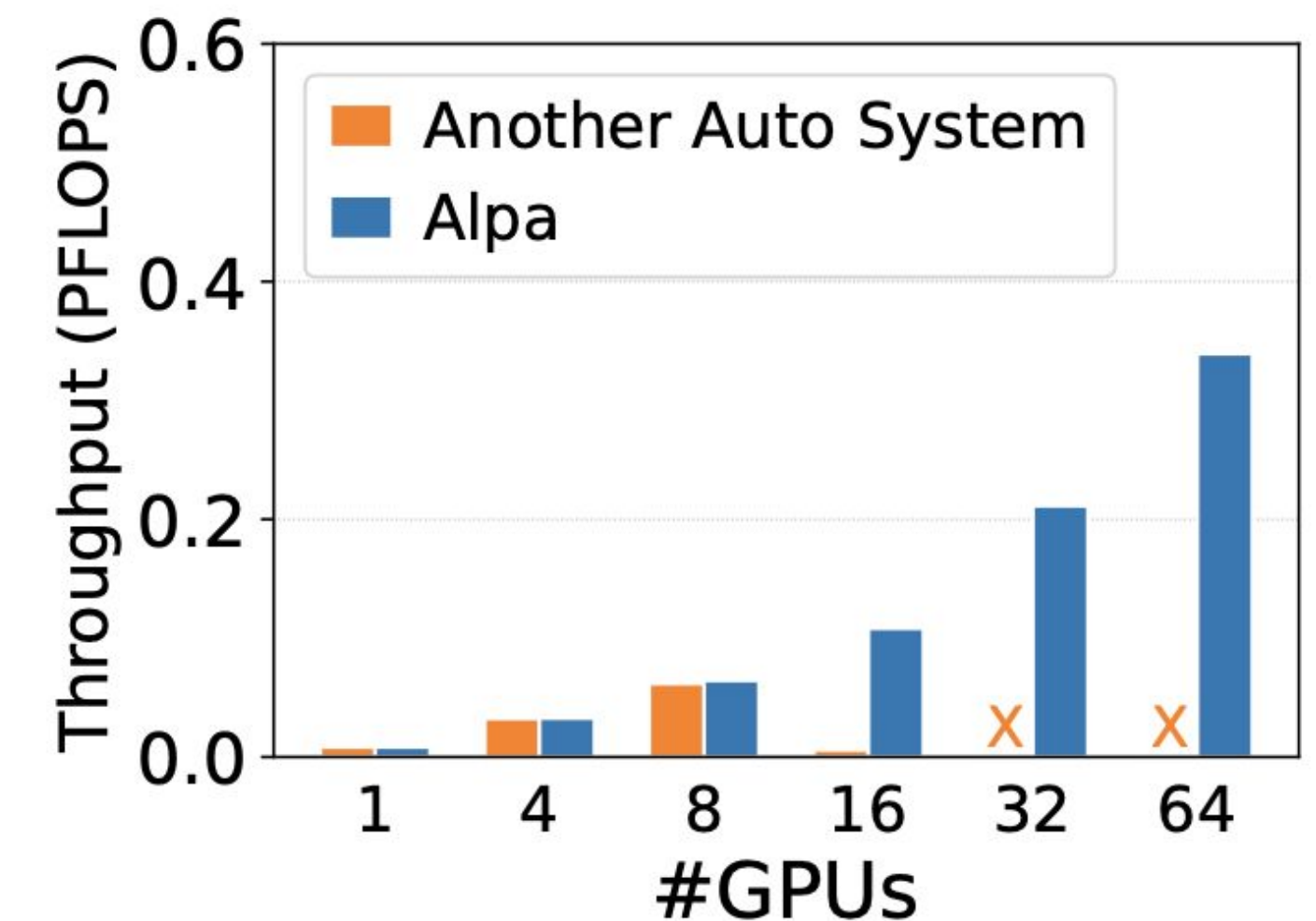
Match specialized manual systems.

GShard MoE (up to 70B)



Outperform the manual baseline by up to 8x.

Wide-ResNet (up to 13B)

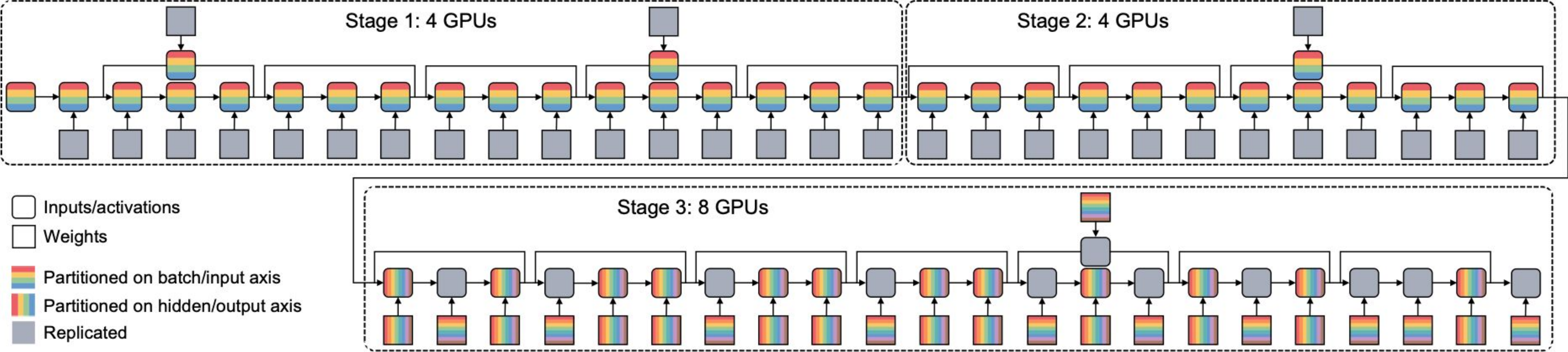


Generalize to models without manual plans.

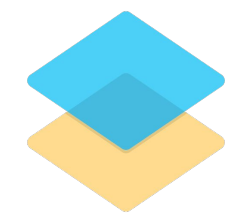
Weak scaling results where the model size grow with #GPUs.

Evaluated on 8 AWS EC2 p3.16xlarge nodes with 8 16GB V100s each (64 GPUs in total).

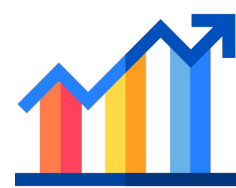
Case Study: Wide-ResNet Partition on 16 GPUs.



@alpa.parallelize: automatic model-parallel training



Hierarchical view: **inter-op** and **intra-op**

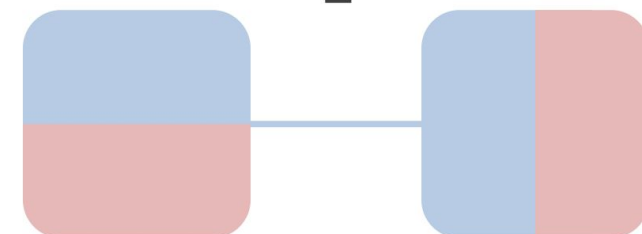


Match or outperform specialized systems



Generalizes to new models

Alpa



alpa.ai



Star

390