HetPipe: Enabling Large DNN Training on (Whimpy) Heterogeneous GPU Clusters through Integration of Pipelined Model Parallelism and Data Parallelism

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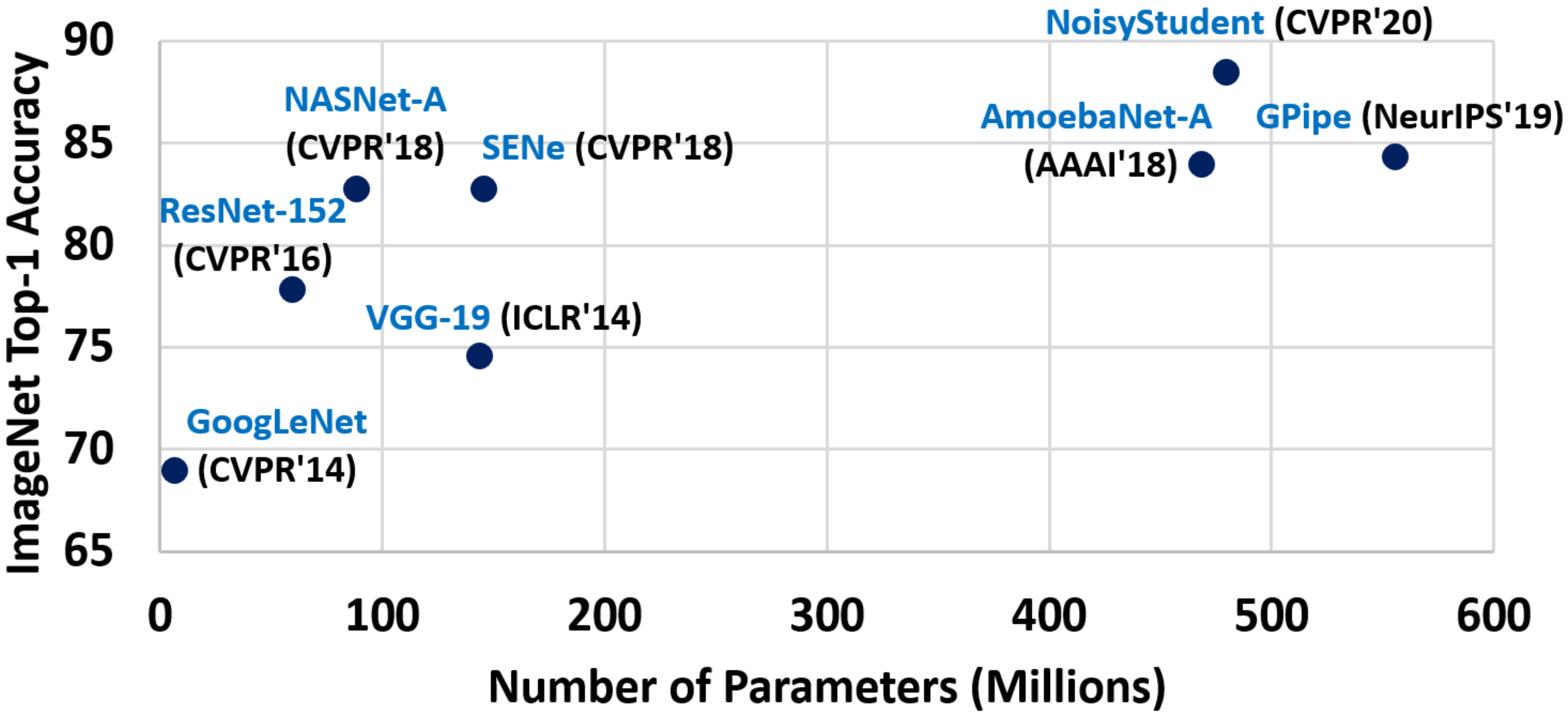
- Motivation & Background
- HetPipe in a Nutshell
- Our System: HetPipe
- Evaluation
- Conclusion

Motivation

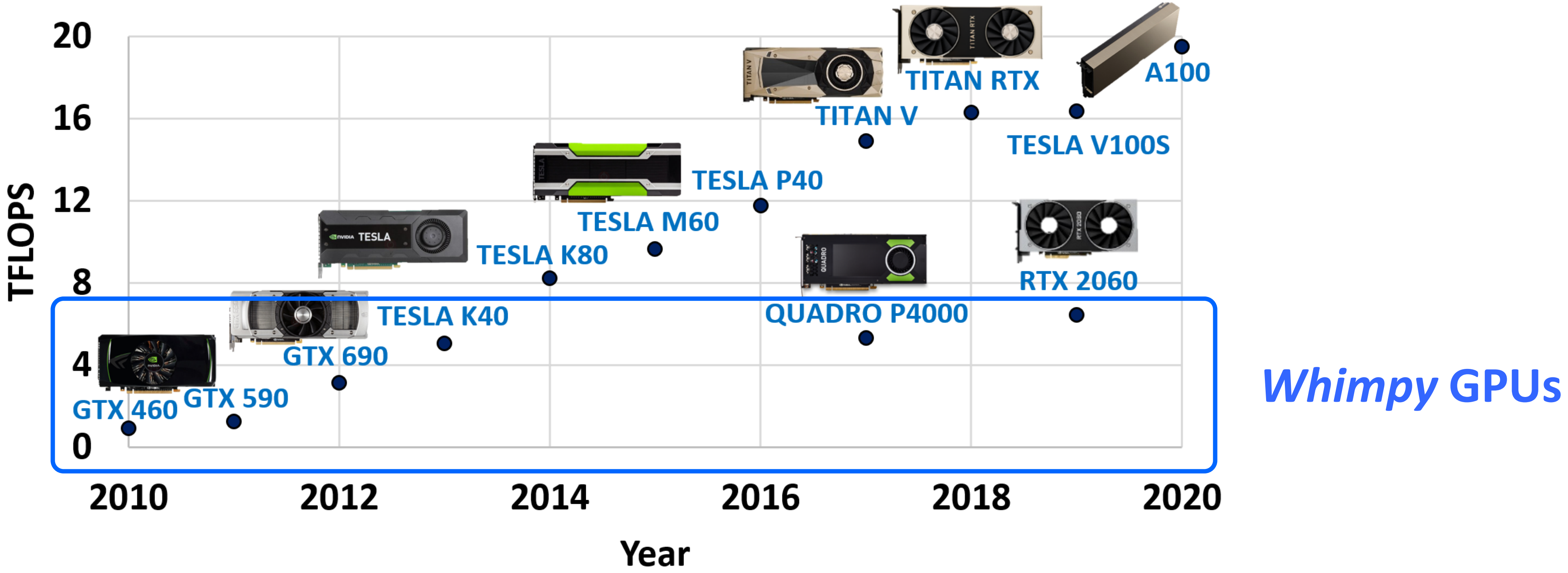
- DNN (Deep Neural Network) models continue to grow



- Need more powerful GPUs for training!

Motivation

- Short release cycle of new GPU architectures

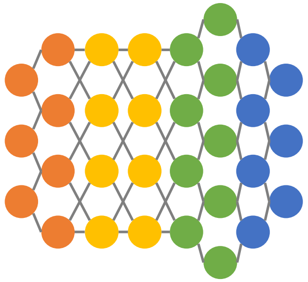


- Use of heterogeneous GPUs is inevitable!
- What to do with *whimpy* GPUs?

DNN Training

Minibatch i
(Training Data)

Forward Pass i



Weight Parameter w

Backward Pass i

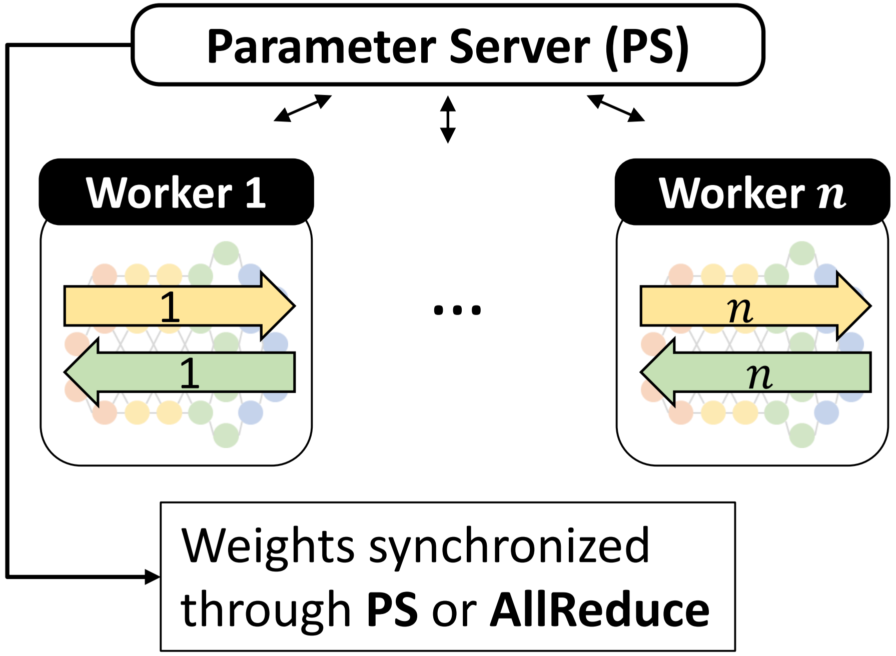
Cat?

Loss

$$w_{i+1} = w_i - \eta \cdot u_i$$

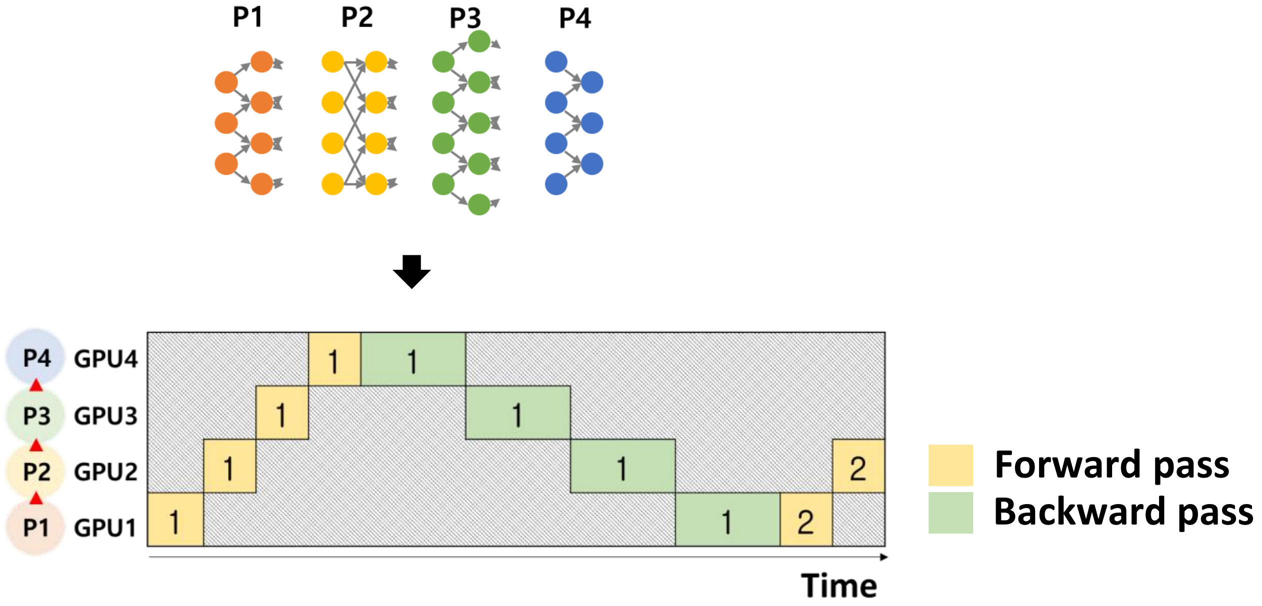
Parallelizing DNN Training

- **Data parallelism (DP)**



- GPU memory limitation

- **Model parallelism (MP)**

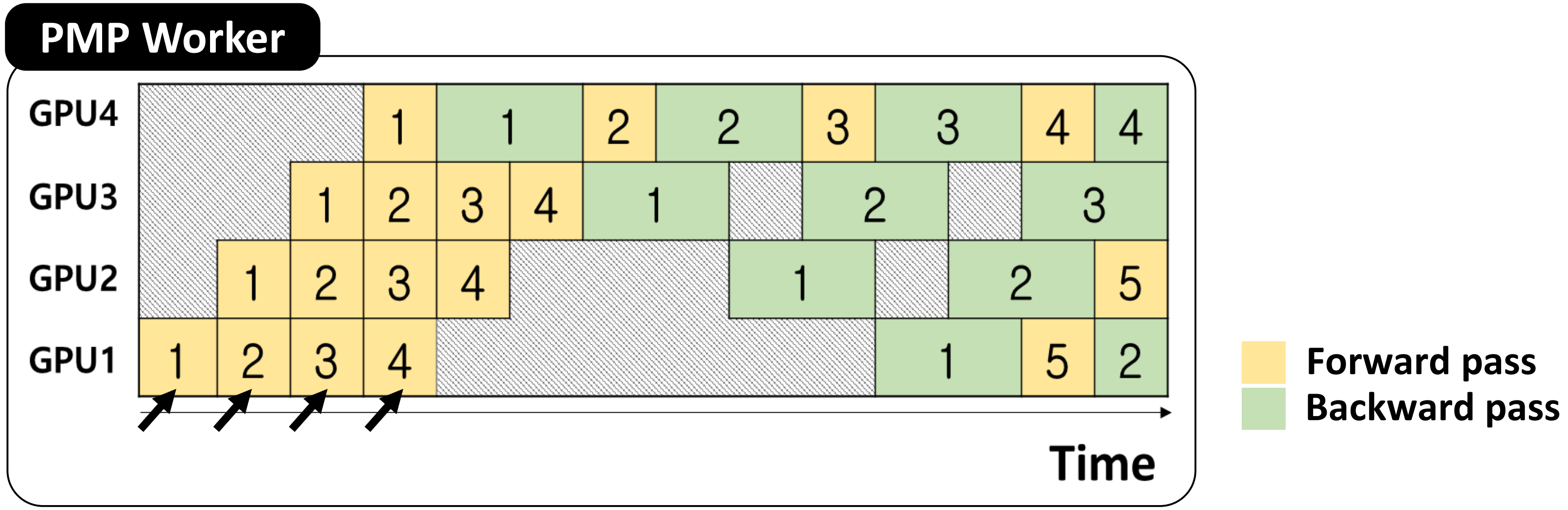


- Low GPU utilization

Parallelizing DNN Training

- **Attempts to improve MP utilization**
  - Pipelined model parallelism (PMP)

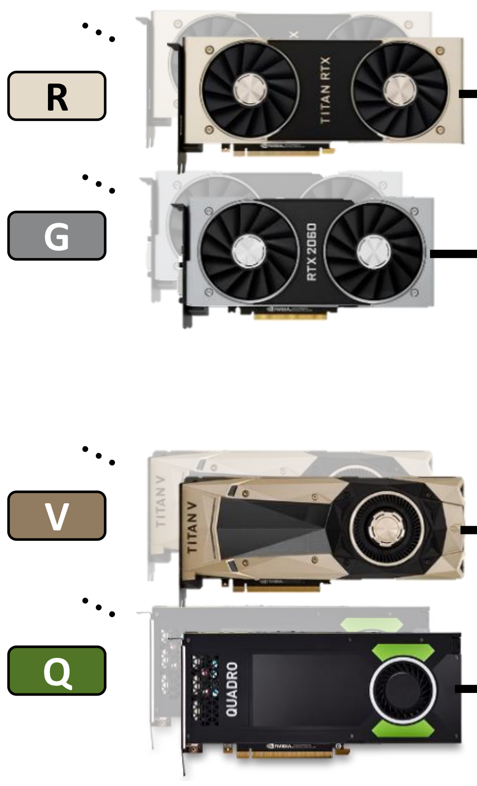
- **PipeDream** [SOSP'19]
- **GPipe** [NIPS'19]

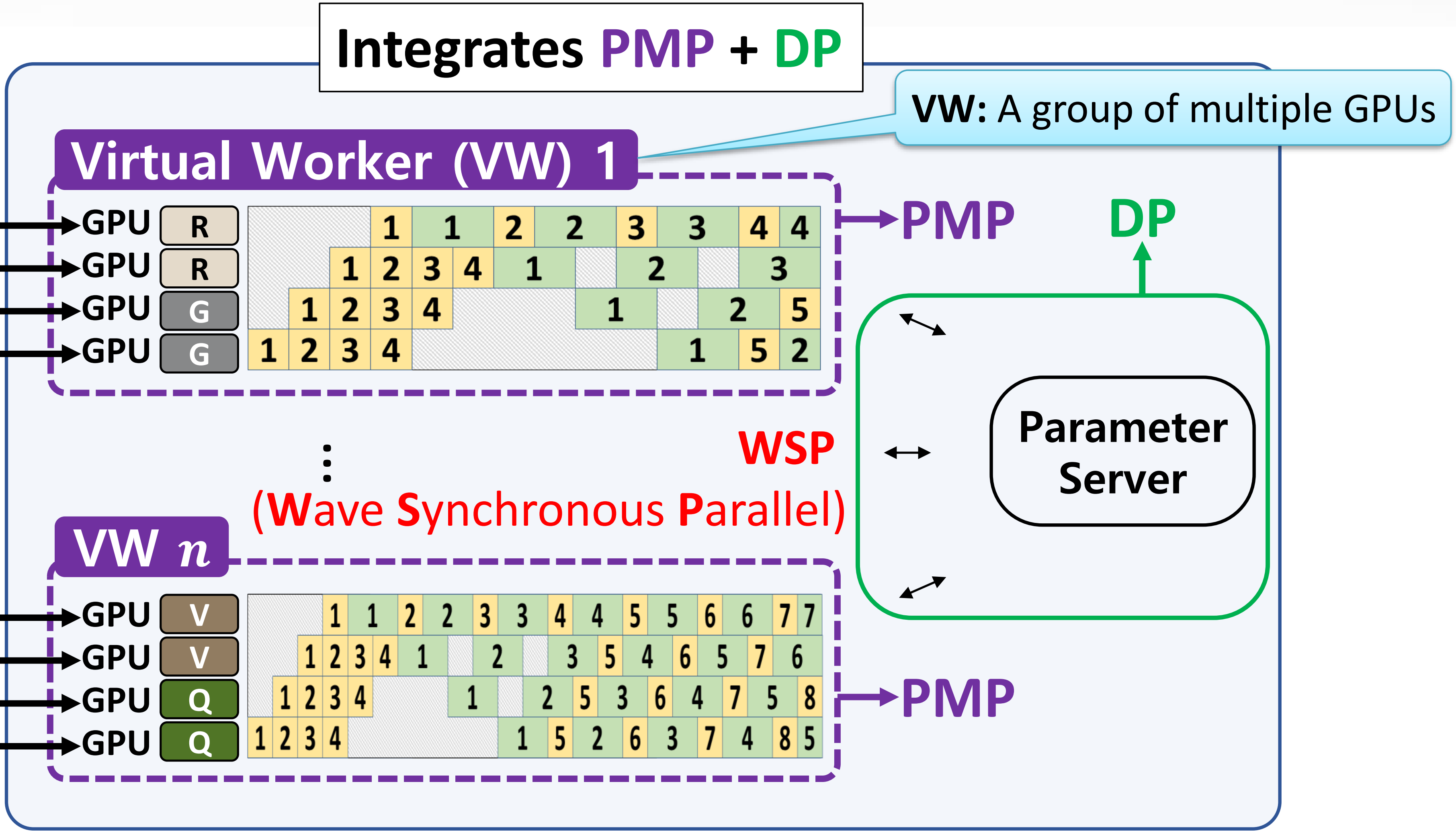


- Designed for homogeneous GPUs
- Designed for a single PMP worker

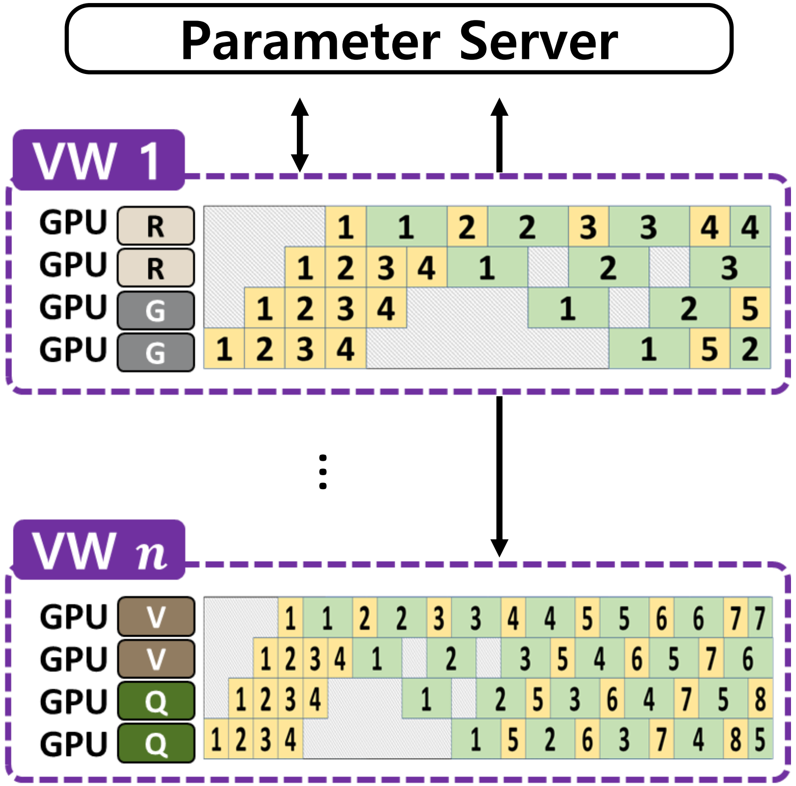
HetPipe in a Nutshell

Support Heterogeneous GPUs





Challenges in integration PMP+DP in Heterogeneous GPUs



- What weight version should be used by each VW to synchronize with other VWs?

- How do we reduce virtual worker stragglers when we consider DP?

⋮

Many more in the paper

HetPipe Contributions

Enable Large DNN Training on Heterogeneous GPUs

Aggregate heterogeneous resources

Reduce the straggler problem

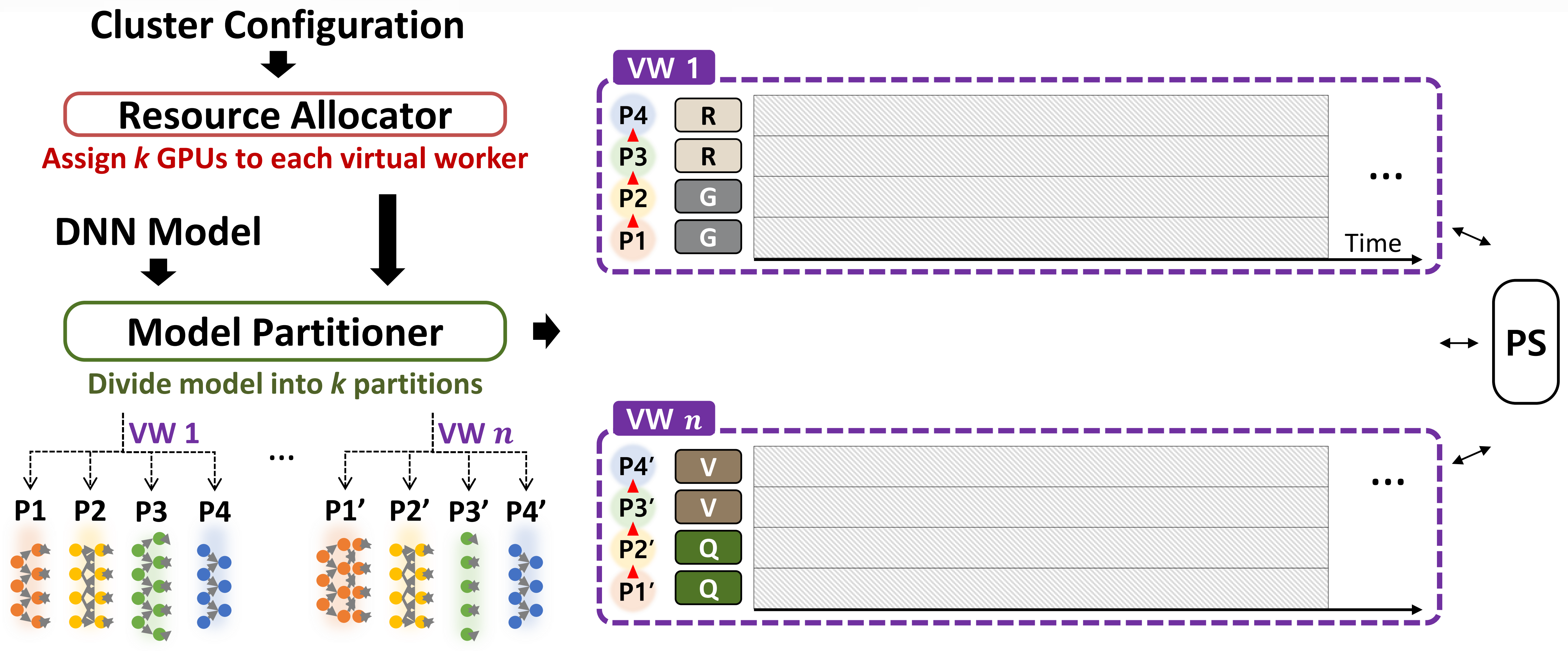
Integrates PMP + DP

Novel parameter synchronization model

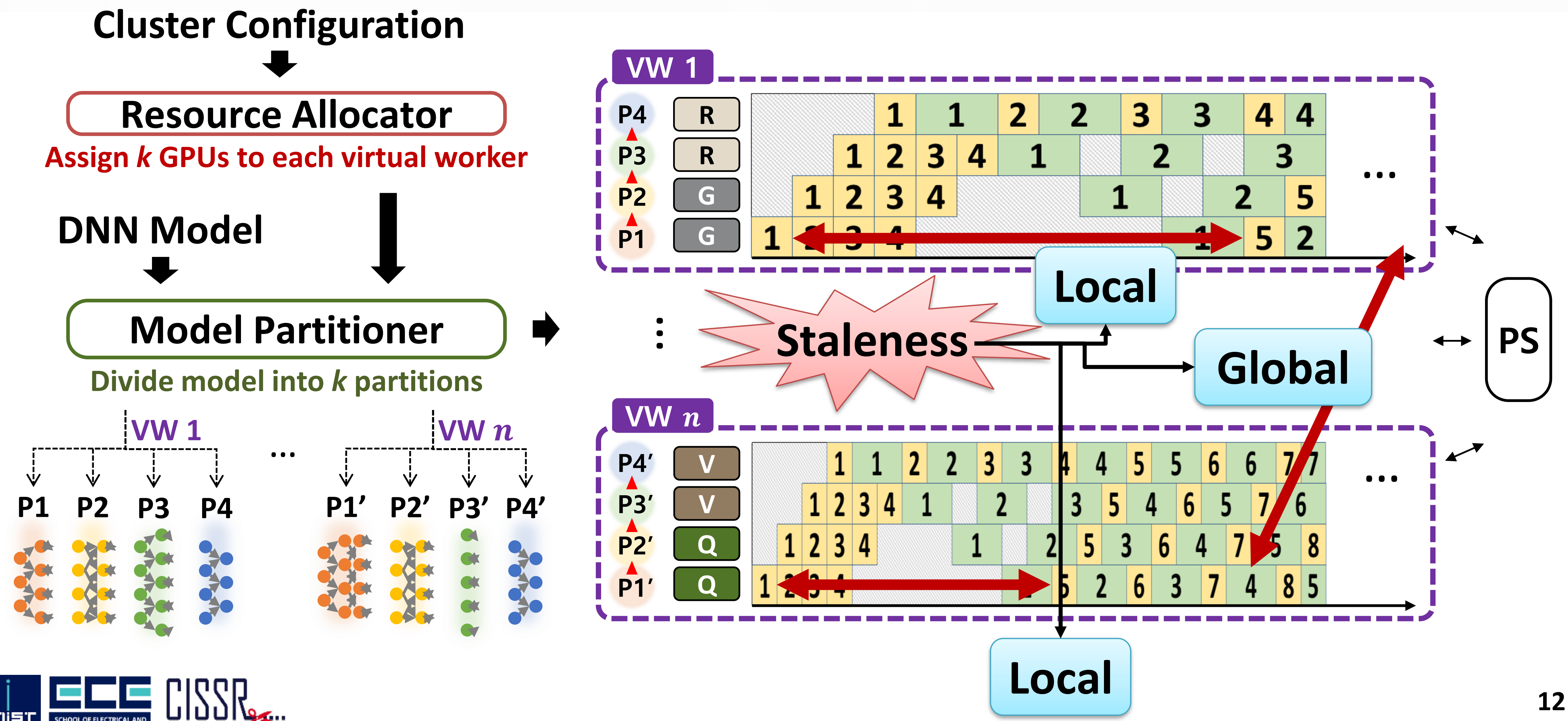
WSP (Wave Synchronous Parallel)

Proof of WSP Convergence

HetPipe Workflow



HetPipe Workflow

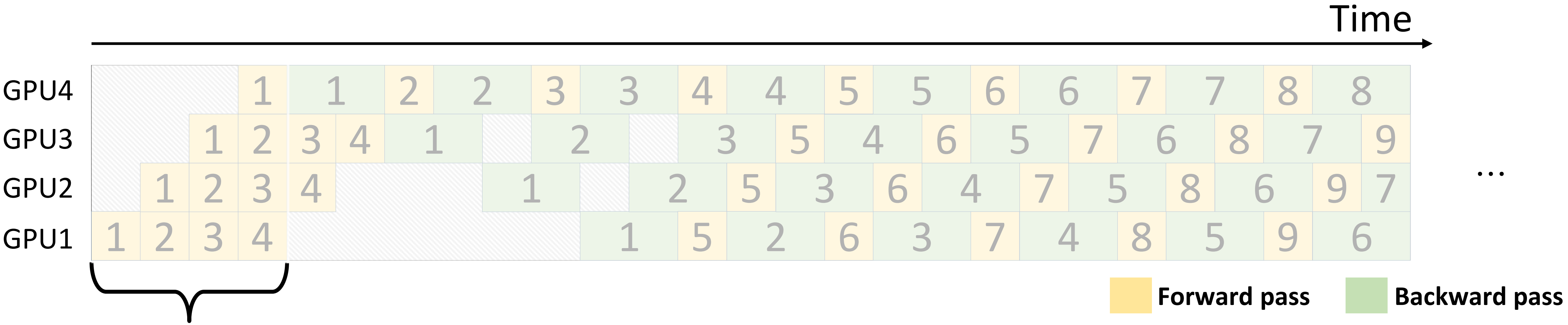


Outline

- Motivation & Background
- HetPipe in a Nutshell
- **Our System: HetPipe**
  - **Pipelined Model Parallelism Within a VW**
  - Data Parallelism with Multiple VWs
- Evaluation
- Conclusion

Pipelined Model Parallelism Within a VW

- **Execution of a virtual worker**



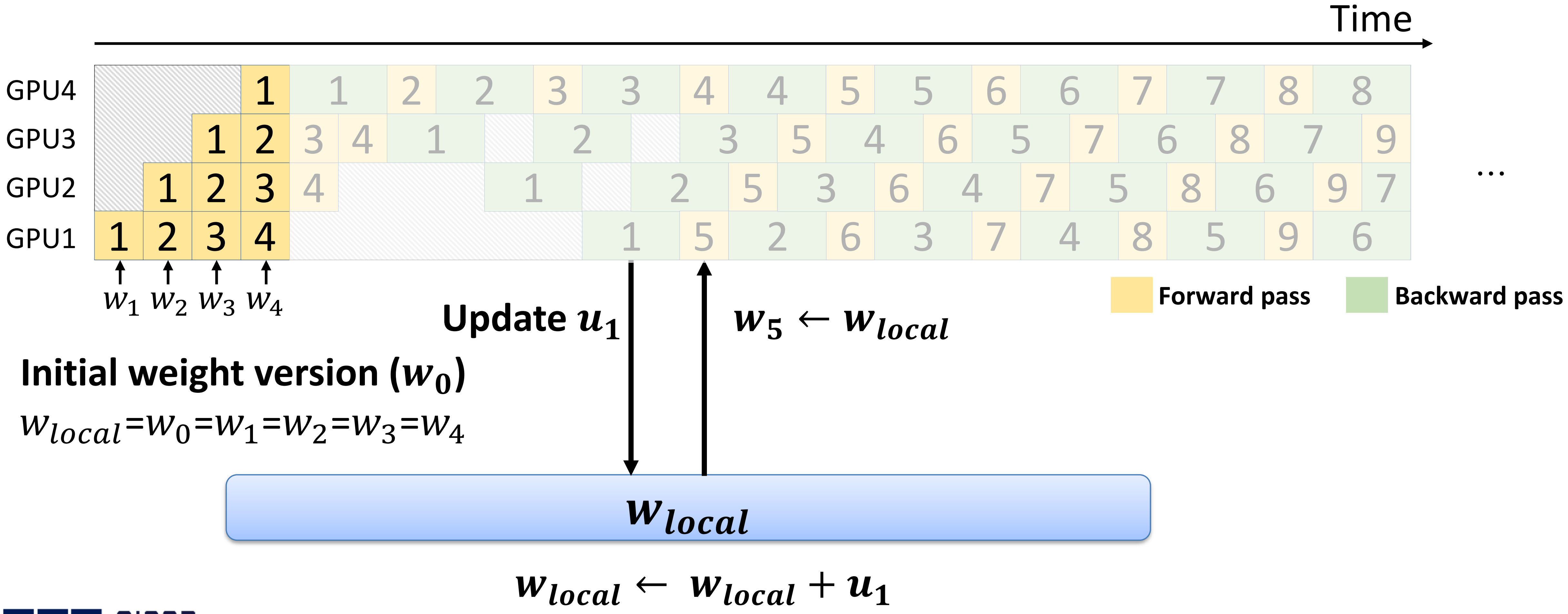
$\boldsymbol{N_m}$ minibatches processed concurrently in pipeline manner

$\boldsymbol{w_{local}}$

$\boldsymbol{W_{local}}$ is a consistent version of weights within a VW

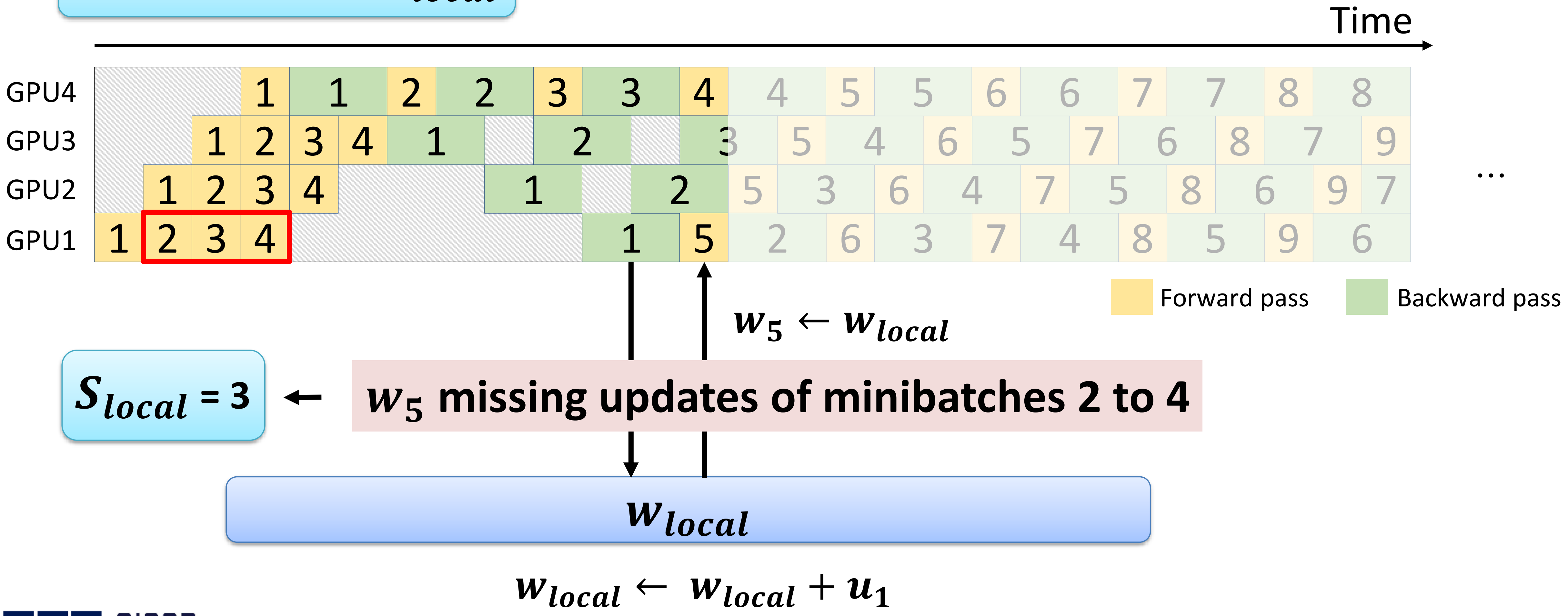
Pipelined Model Parallelism Within a VW

- **Weight management procedure**



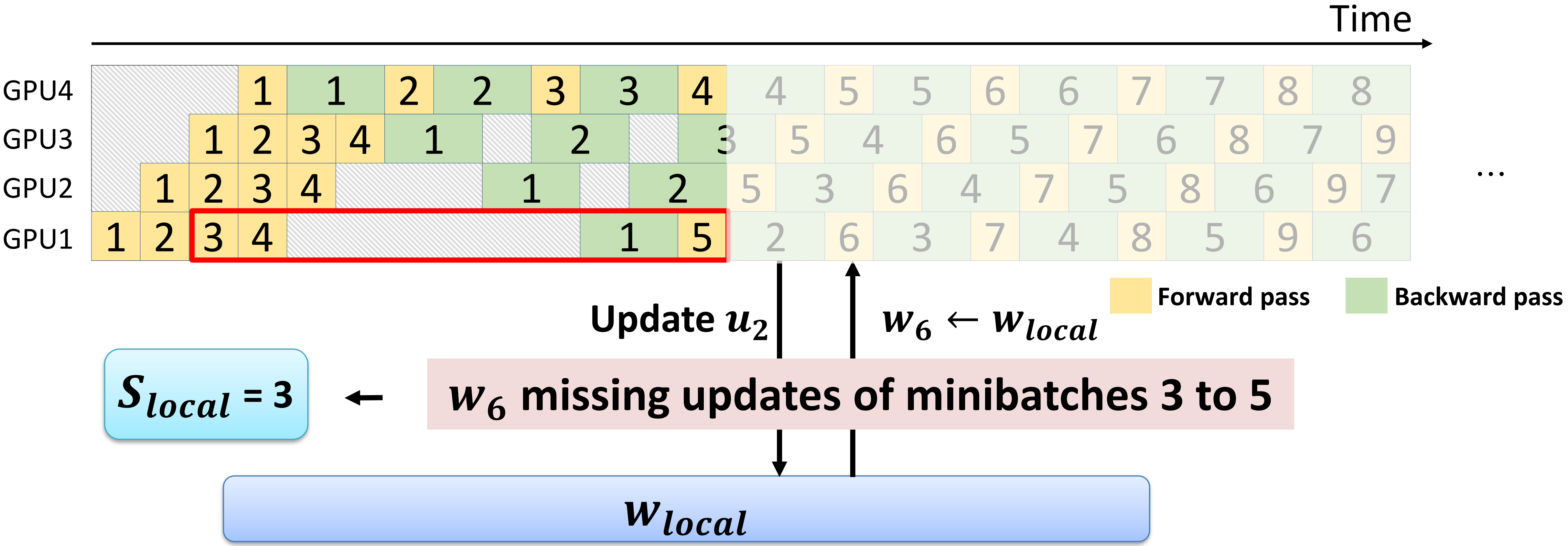
Pipelined Model Parallelism Within a VW

- Local staleness (S_{local}): maximum missing updates



Pipelined Model Parallelism Within a VW

- **Local staleness (S_{local}): maximum missing updates**



$w_{local} \leftarrow w_{local} + u_2$

$\boxed{w_0 + u_1}$

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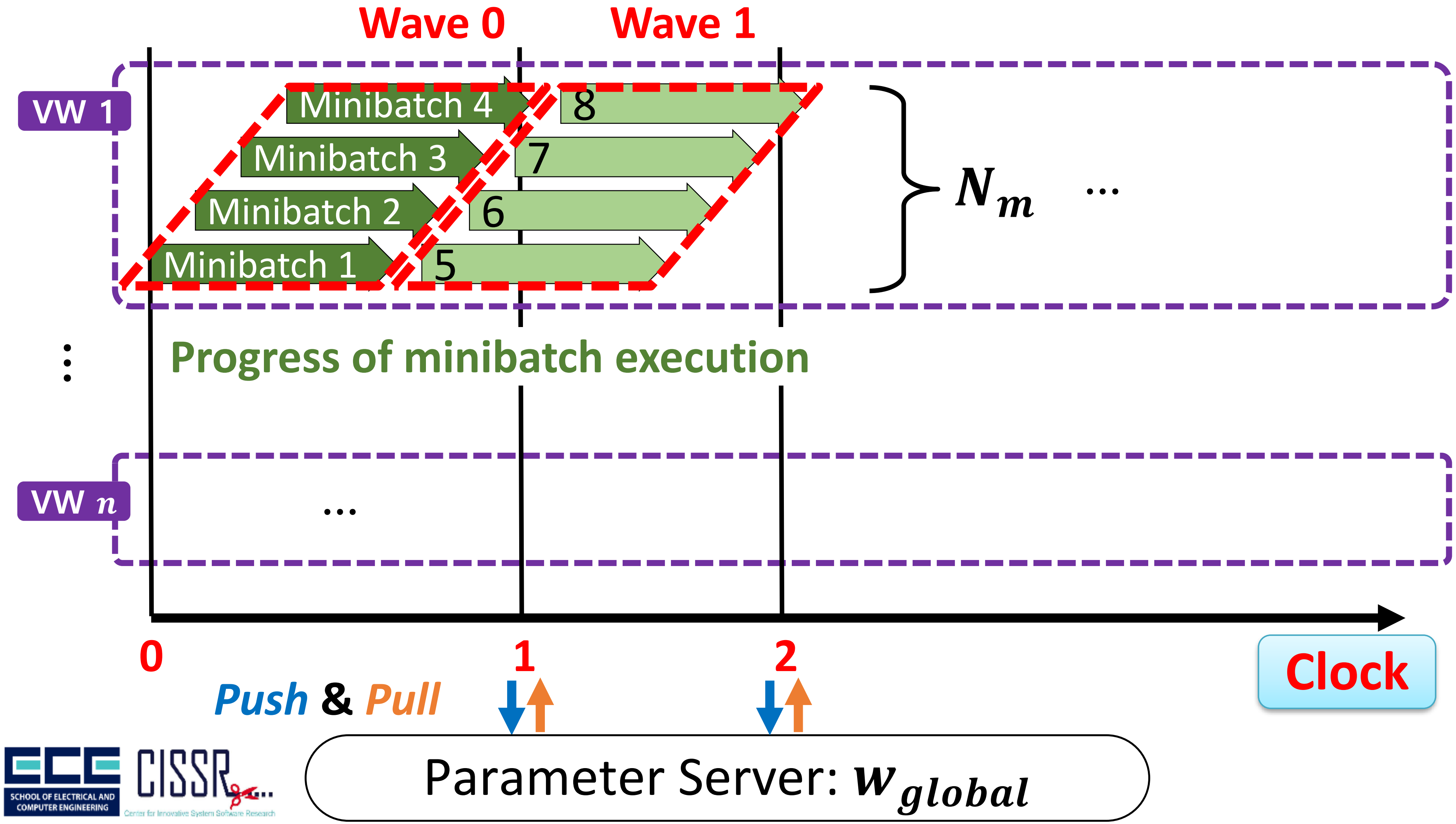
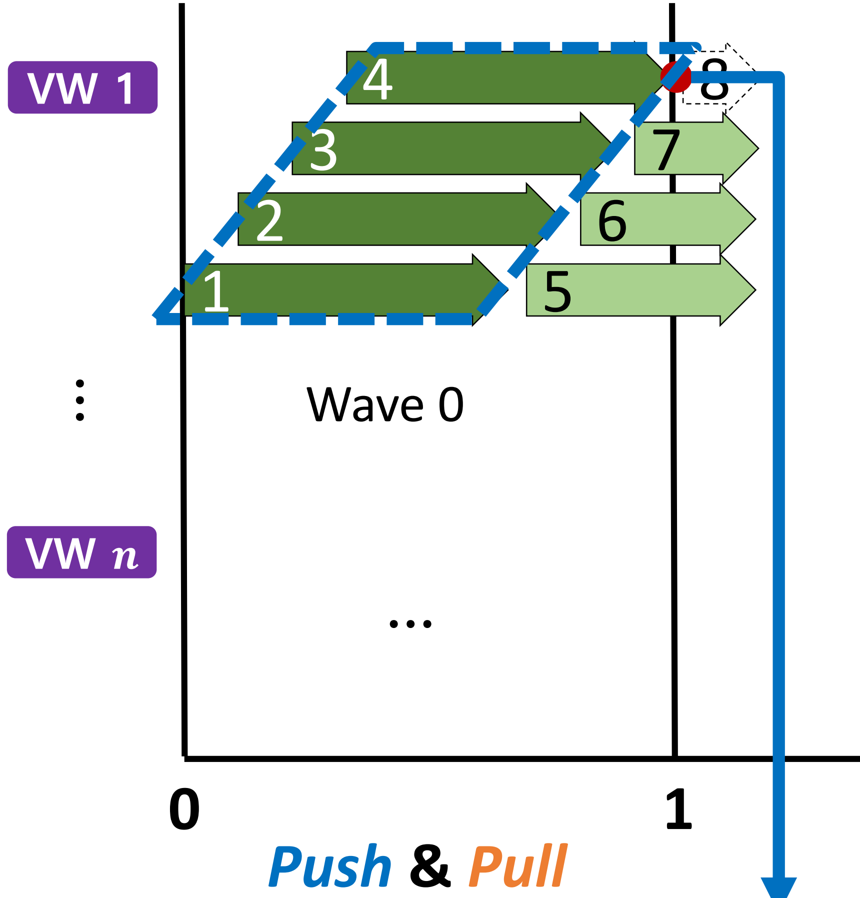
Data Parallelism with Multiple VWs

Wave: Sequence of concurrently executing N_m minibatches



Data Parallelism with Multiple VWs

- *Push* occurs every clock



Blocked minibatch 8

Push aggregated updates of wave0 ($\tilde{u}$)

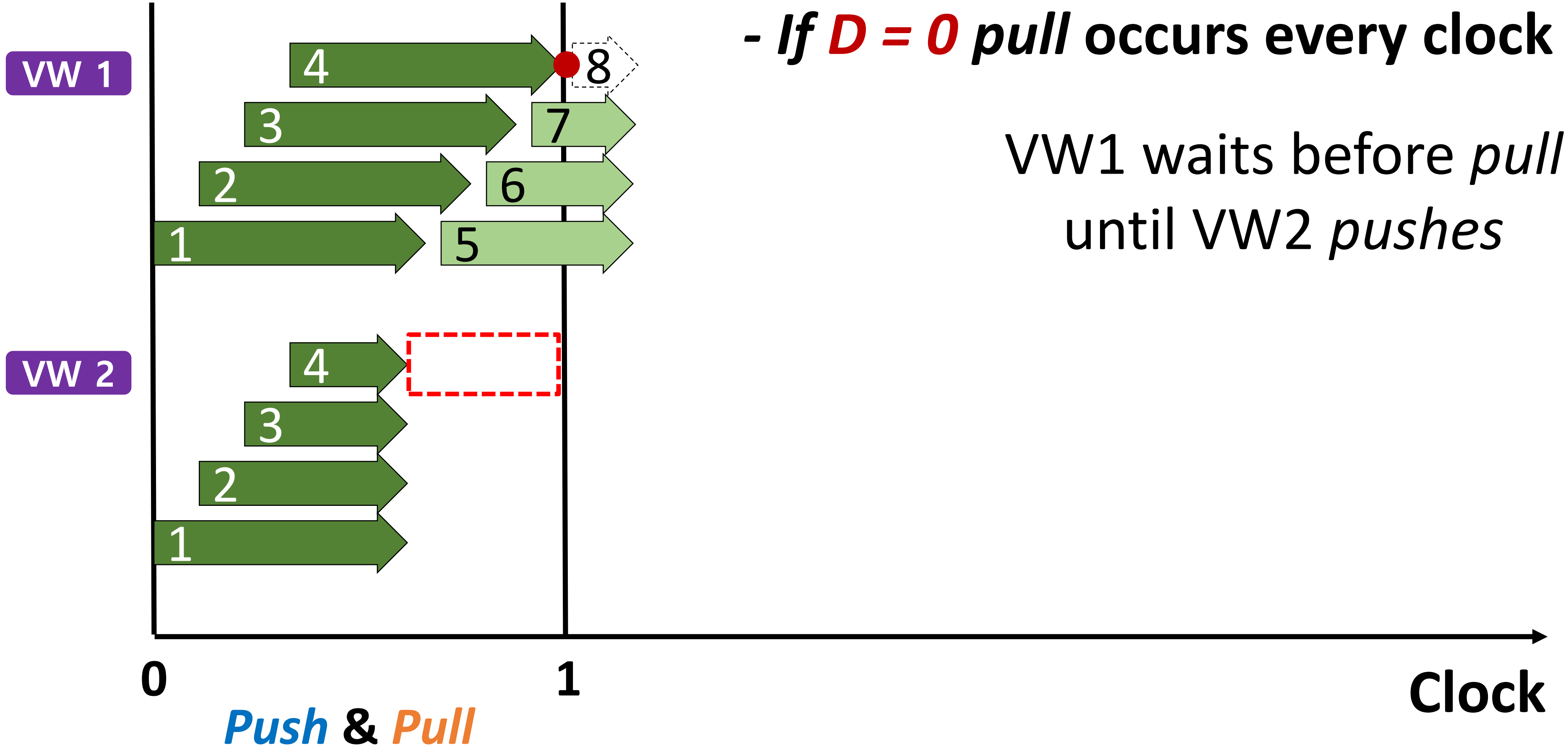
$$\tilde{u} = u_1 + u_2 + u_3 + u_4$$

$$\boldsymbol{w_{global}} \leftarrow \boldsymbol{w_{global}} + \boldsymbol{\tilde{u}}$$

Parameter Server: $\boldsymbol{w_{global}}$

Data Parallelism with Multiple VWs

- *Pull* occurs intermittently - Depending on user defined *clock distance D*
  - *If D = 0 pull* occurs every clock

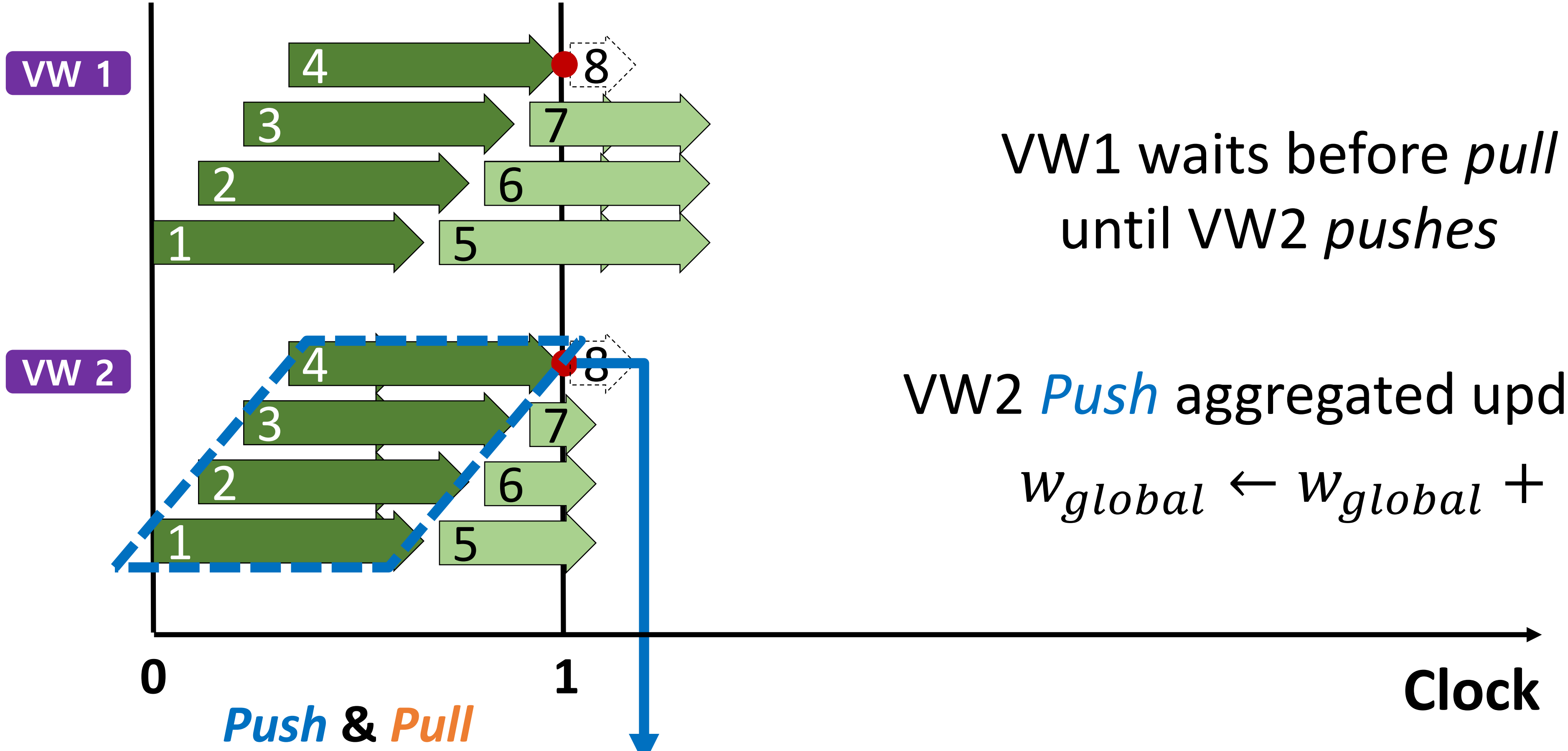


VW1 waits before *pull* until VW2 *pushes*

Parameter Server: w_{global}

Data Parallelism with Multiple VWs

- *Pull* occurs intermittently - Depending on user defined *clock distance D*



If D = 0

VW1 waits before *pull*
until VW2 *pushes*

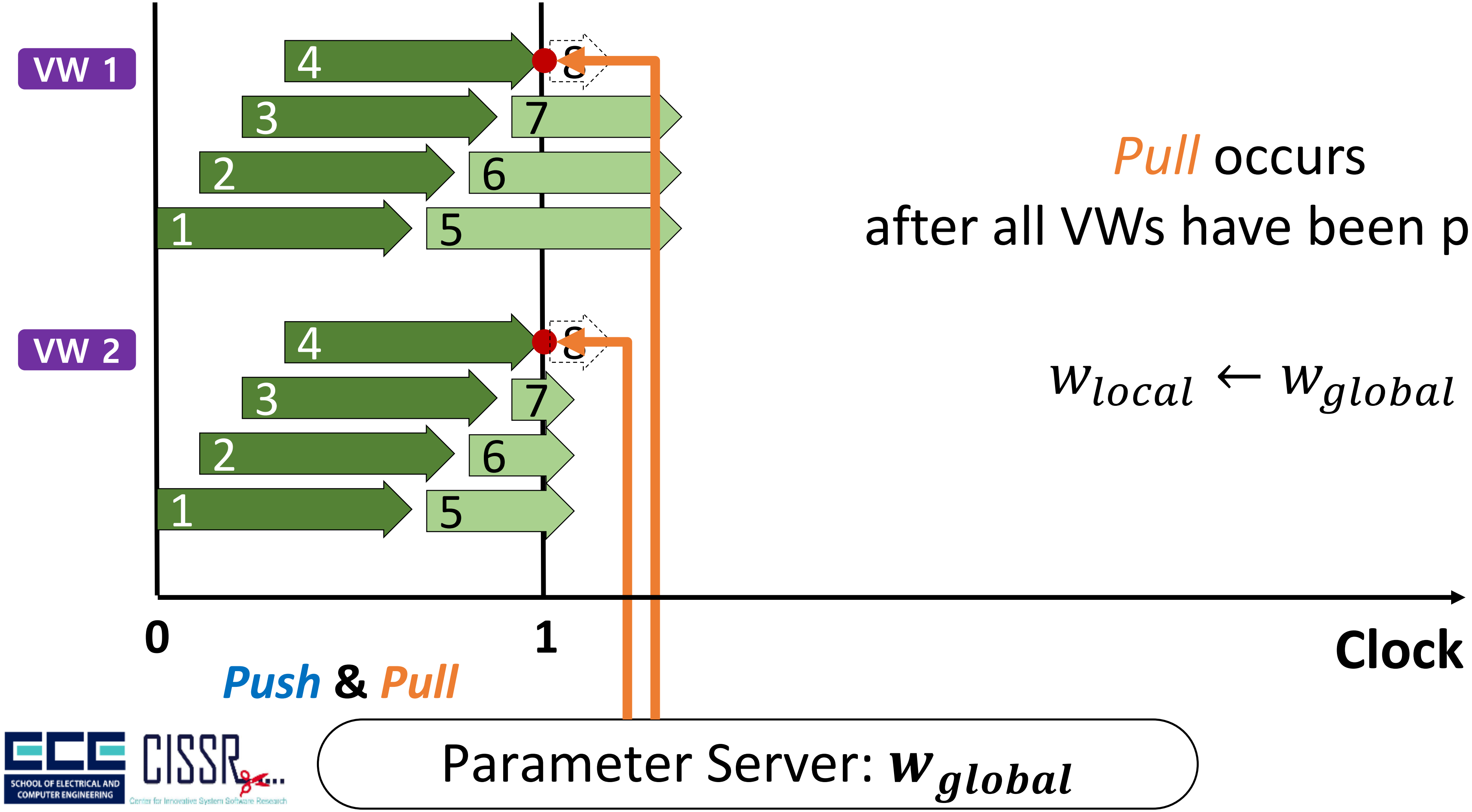
VW2 *Push* aggregated updates ($\tilde{u}$)

$$w_{global} \leftarrow w_{global} + \tilde{u}$$

Parameter Server: $\boldsymbol{w}_{global}$

Data Parallelism with Multiple VWs

- ***Pull* occurs intermittently - Depending on user defined *clock distance D***



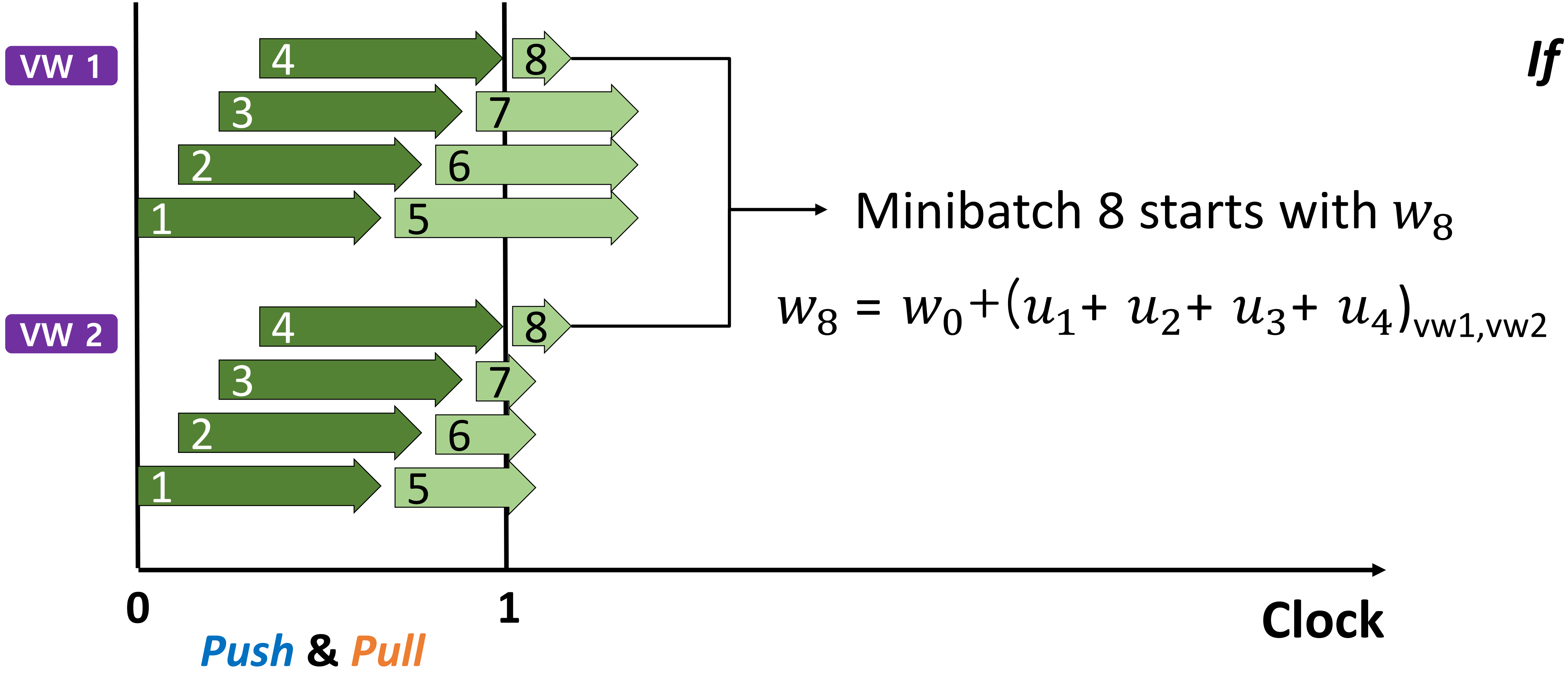
If D = 0

Pull occurs
after all VWs have been pushed

$$w_{local} \leftarrow w_{global}$$

Data Parallelism with Multiple VWs

- *Pull* occurs intermittently - Depending on user defined *clock distance D*

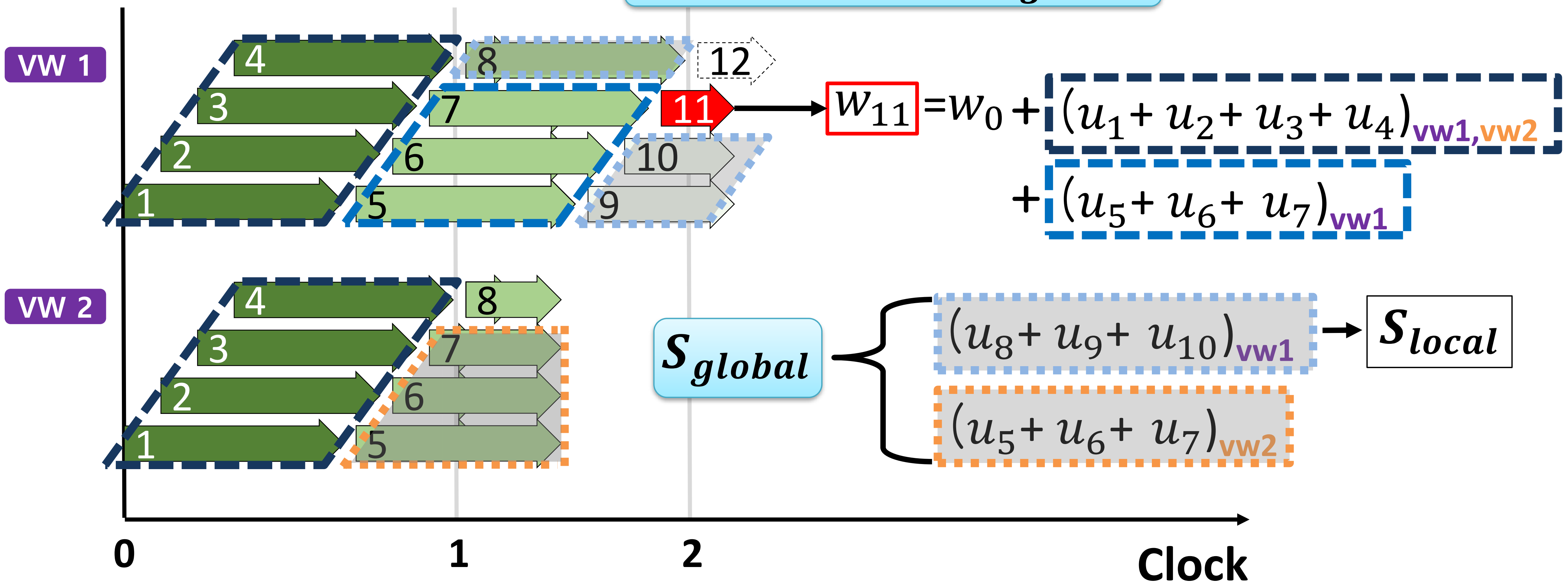


If D = 0

Parameter Server: $\boldsymbol{w_{global}}$

Data Parallelism with Multiple VWs

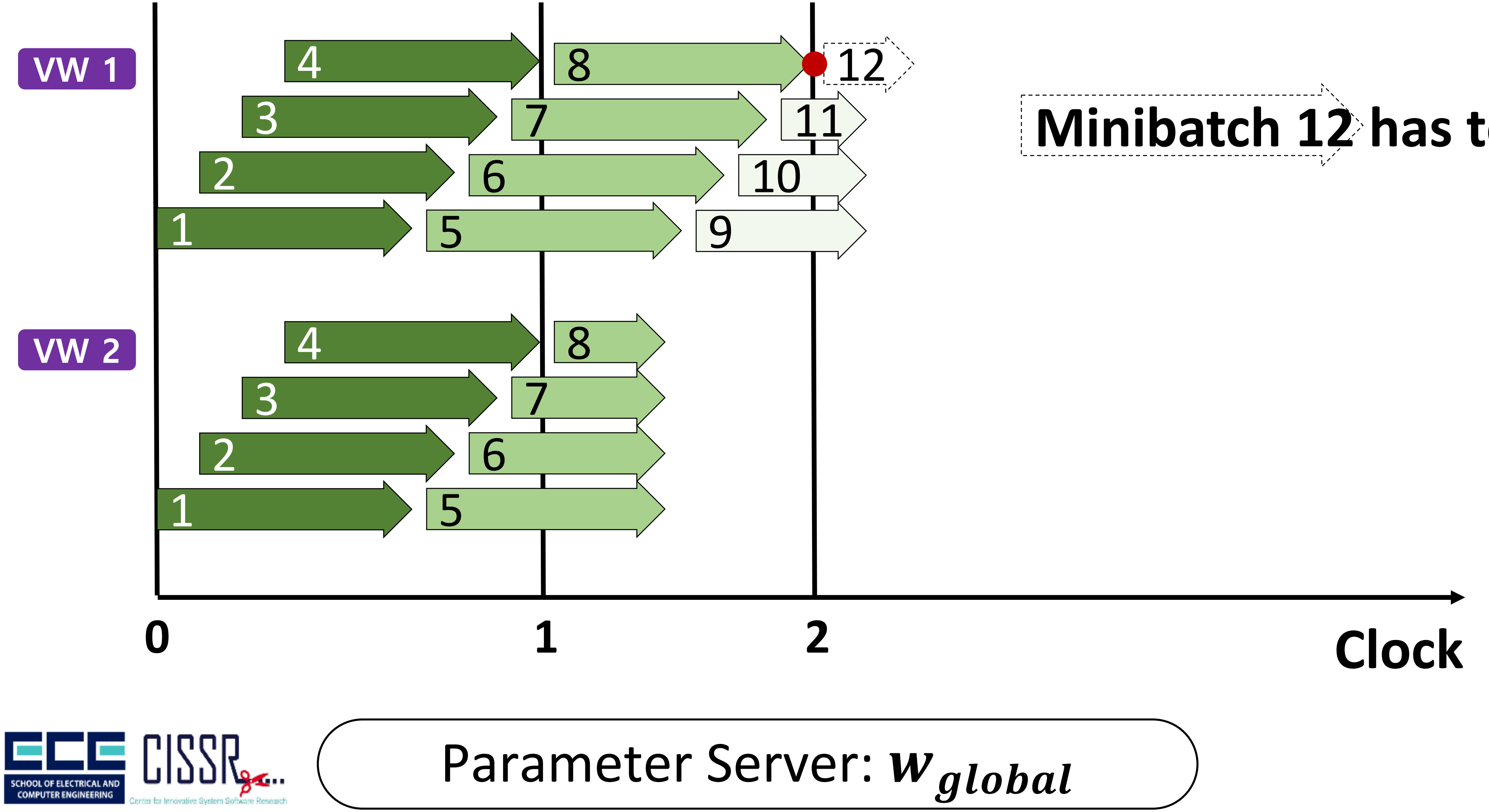
- Local staleness (S_{local}) and global staleness (S_{global}) with WSP



$$w_{global} = w_0 + (u_1 + u_2 + u_3 + u_4)_{vw1,vw2}$$

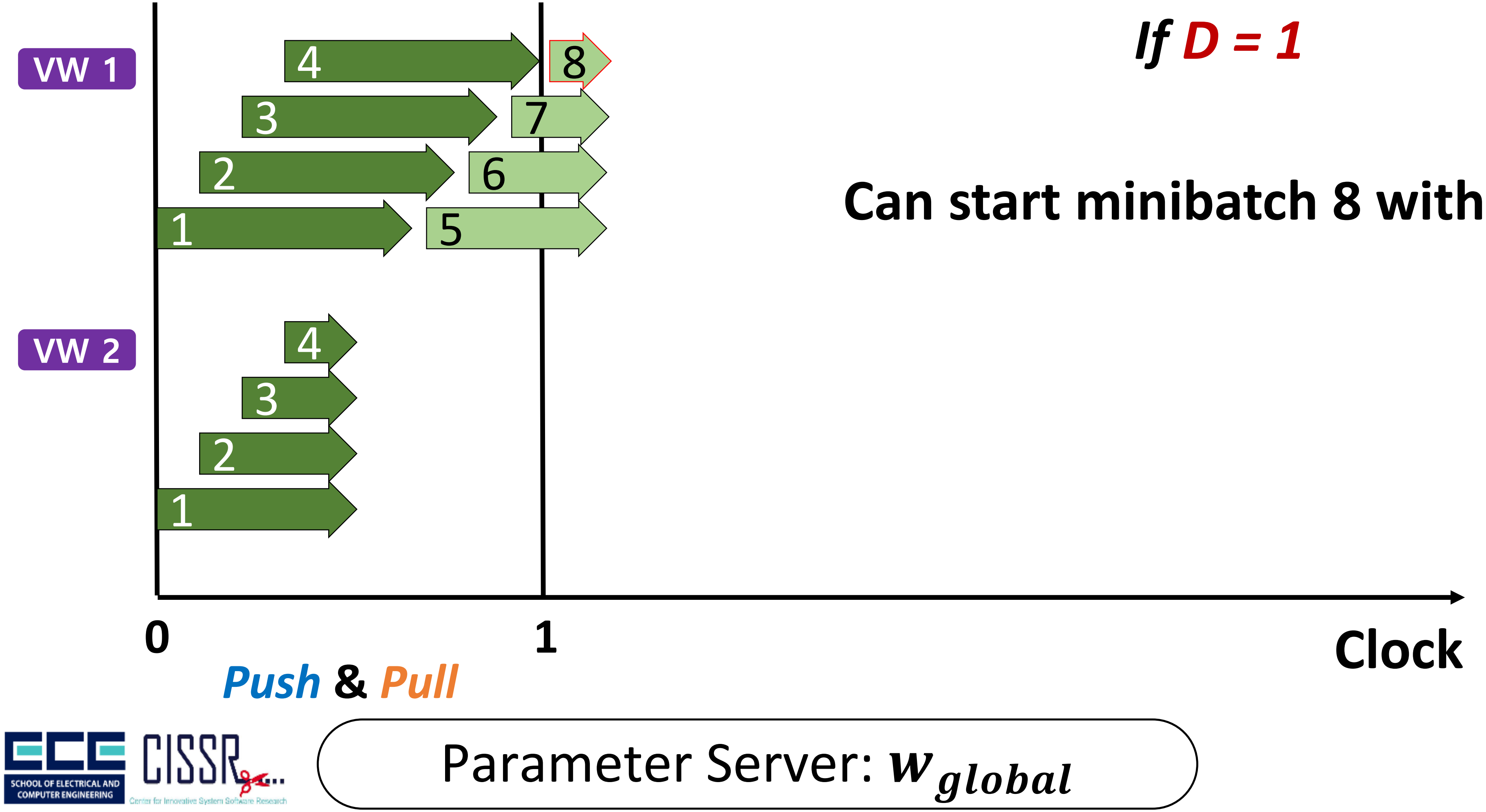
Data Parallelism with Multiple VWs

- **Local staleness (S_{local}) and global staleness (S_{global}) with WSP**



Data Parallelism with Multiple VWs

- Example of clock distance threshold *D*

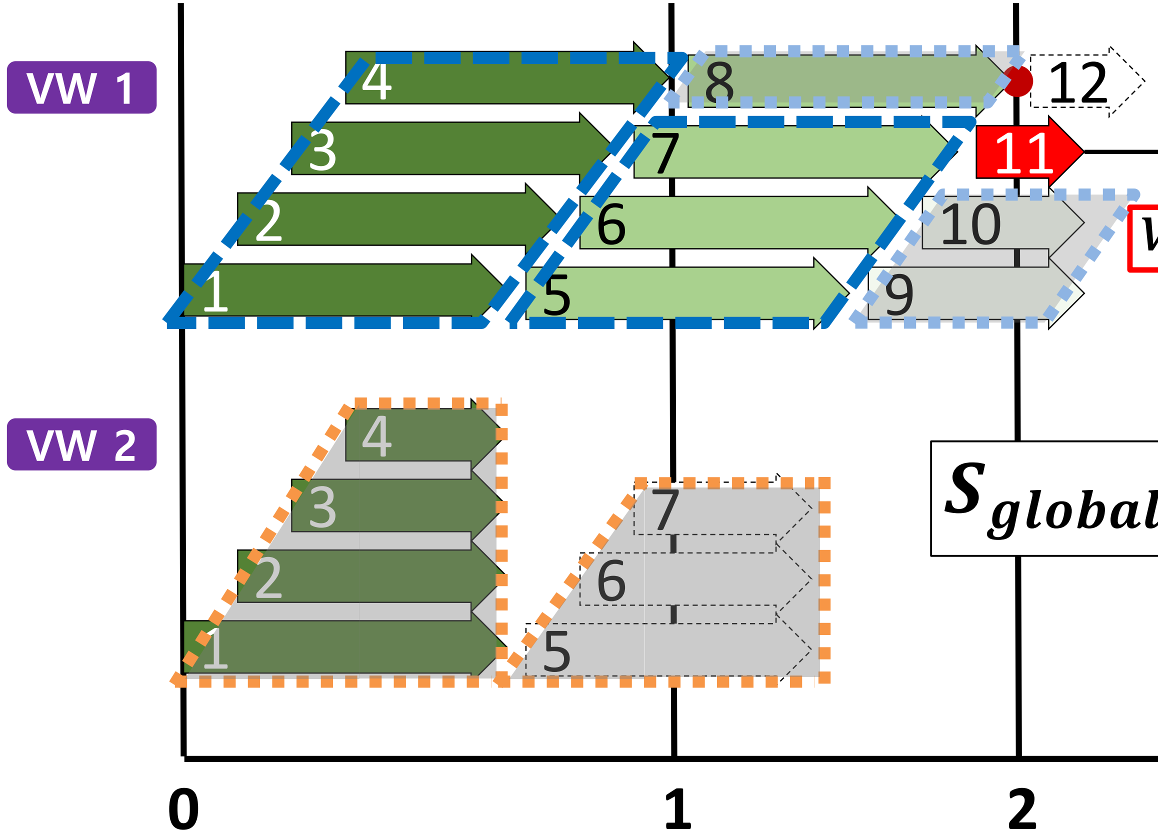


If D = 1

Can start minibatch 8 without *pull*

Data Parallelism with Multiple VWs

- **Example of clock distance threshold *D***



Clock

If D = 1

Minibatch 12 has to wait

$$\boxed{w_{11}} = w_0 + (u_1 + u_2 + u_3 + u_4 + u_5 + u_6 + u_7)_{vw1}$$

$$S_{global} = \begin{cases} (u_8 + u_9 + u_{10})_{vw1} \rightarrow \boxed{S_{local}} \\ (u_1 + u_2 + u_3 + u_4 + u_5 + u_6 + u_7)_{vw2} \end{cases}$$

$$w_{global} = w_0$$

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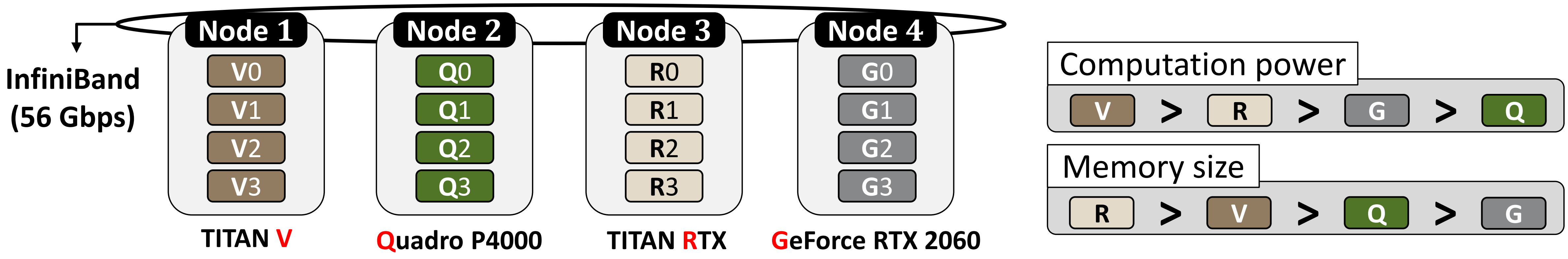
- **Evaluation**
  - **Setup**
  - **Resource Allocation for Virtual Workers**
  - **Results**
- Conclusion

Evaluation Setup

- **Cluster setup - 4 heterogeneous GPU nodes**

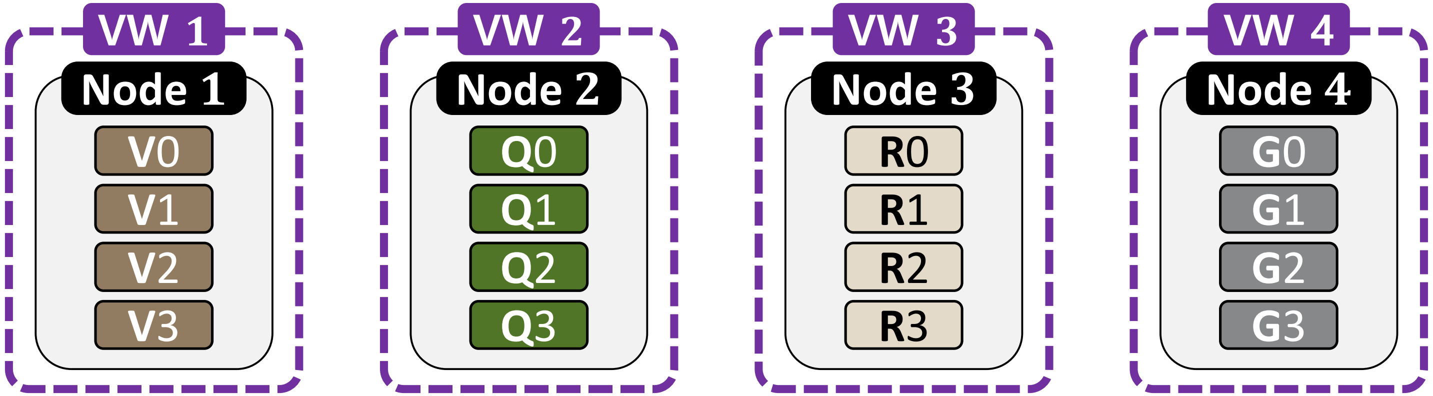


- **Two DNN models**

	ResNet-152	VGG-19
Dataset, minibatch size	ImageNet, 32	
Model parameter size	230 MB	548 MB
Characteristic	Large activation output	Large parameter size

Resource Allocation for Virtual Workers: NP, ED, HD

- **NP (Node Partition)**

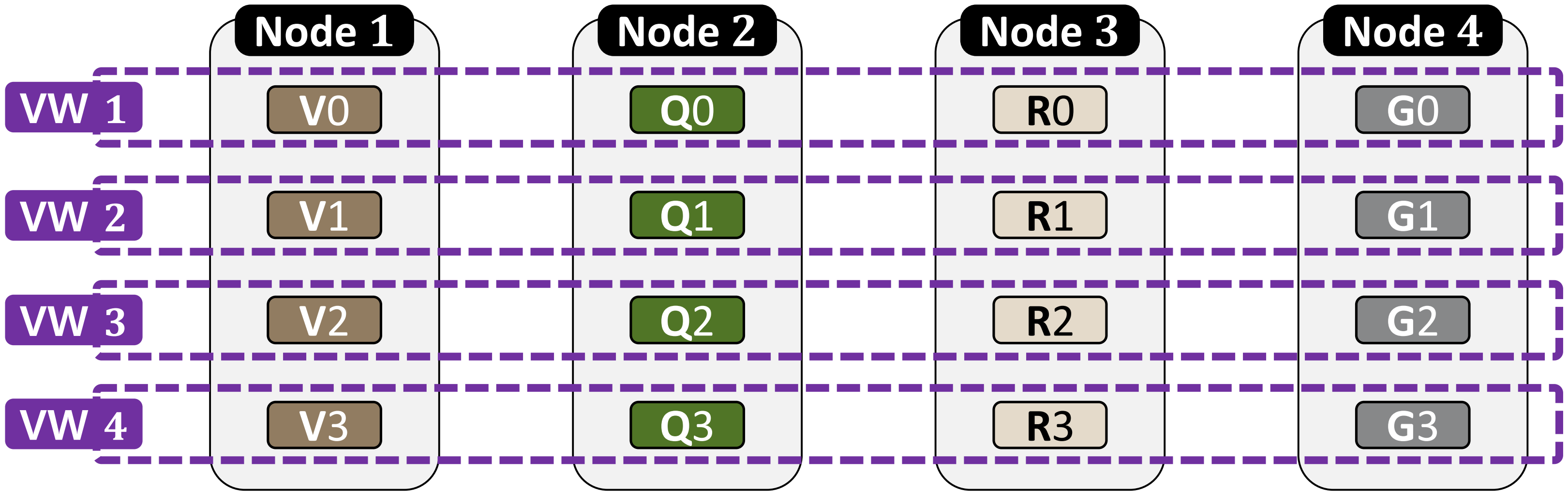


- Minimum communication overhead within VW

- Performance of each virtual worker varies
- Straggler may degrade performance with DP

Resource Allocation for Virtual Workers: NP, ED, HD

- ED (Equal Distribution)

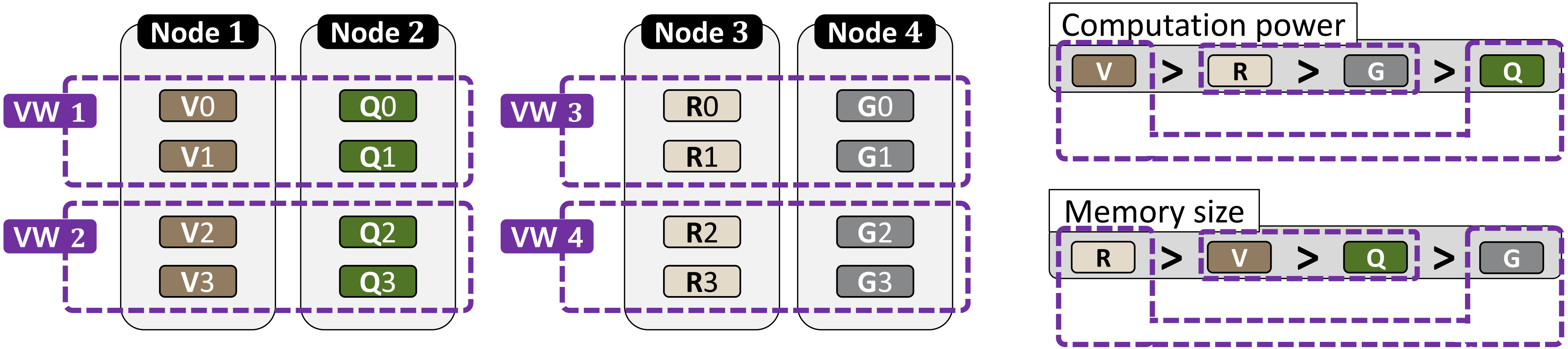


- Performance will be the same across the VWs
- Mitigates the straggler problem

- High communication overhead within each VW

Resource Allocation for Virtual Workers: NP, ED, HD

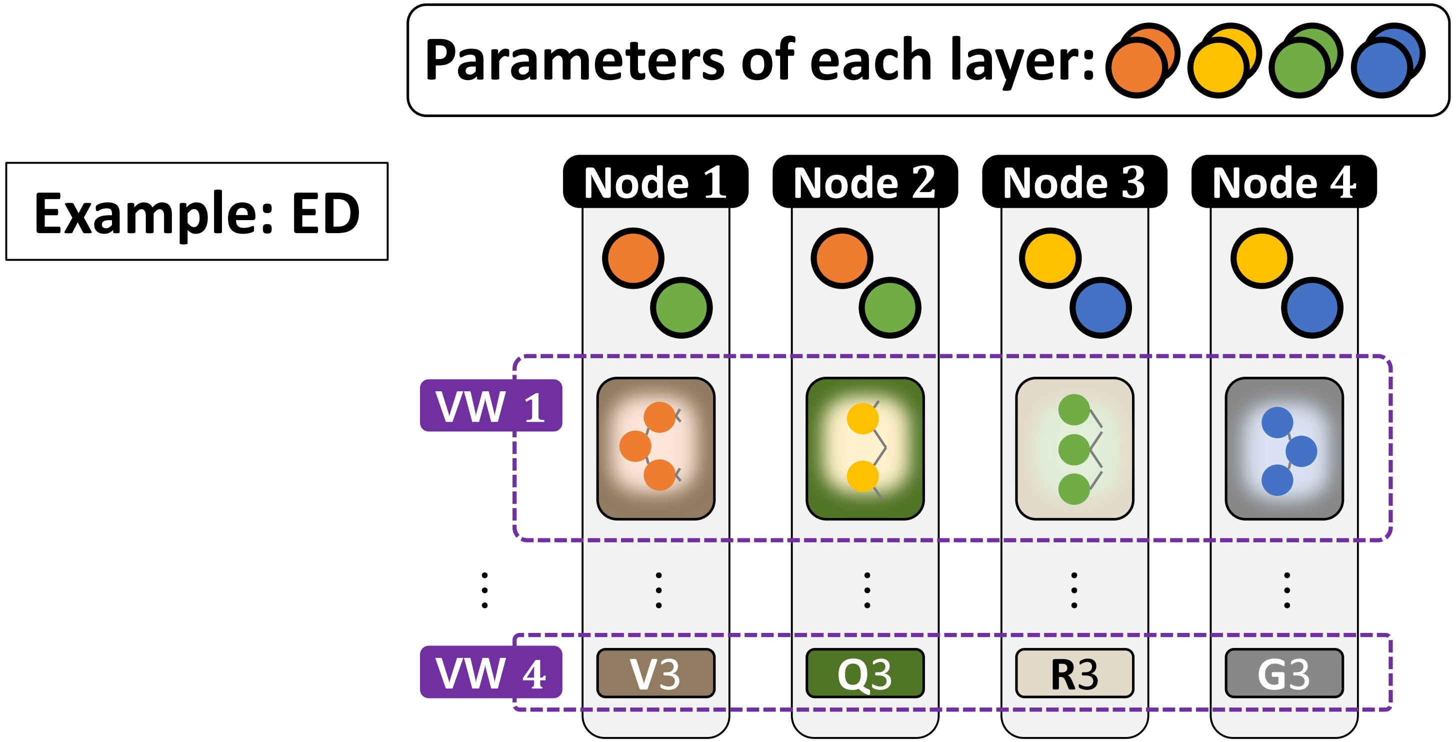
- HD (Hybrid Distribution)



- Mitigates the straggler problem
- Reduces communication overhead within each VW

Parameter Placement

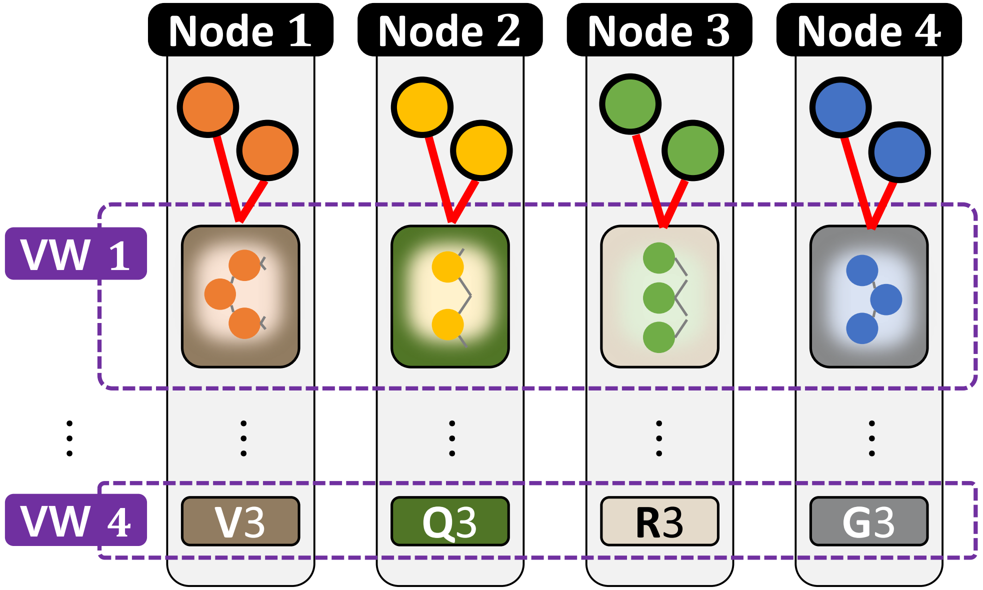
- **Round-robin policy (default)**
  - Can be used in all three policies: **NP**, **ED**, and **HD**

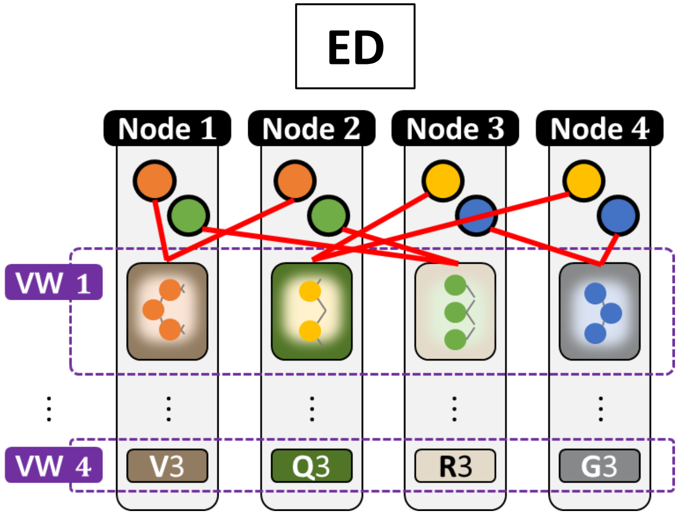


Parameter Placement

- Local placement policy
  - ED-local

Parameters of each layer:



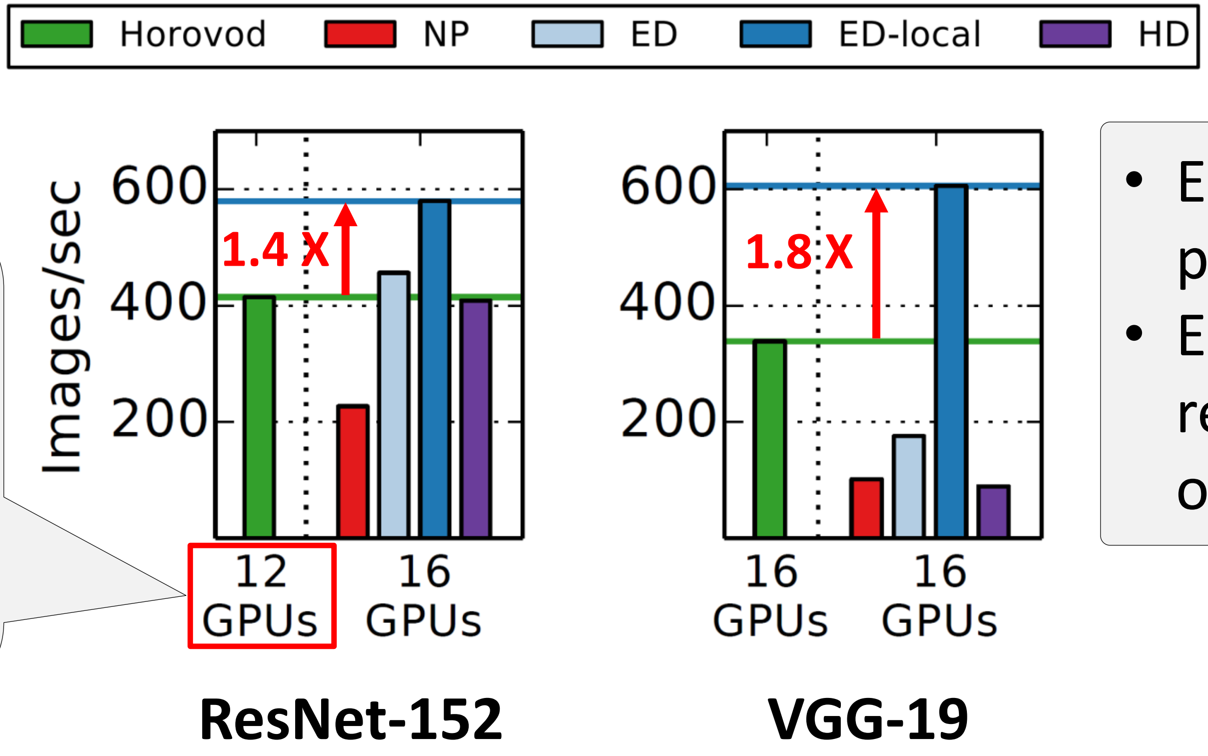


- Significantly reduces communication overhead

- Parameter communication occurs

Compare Throughput with Horovod

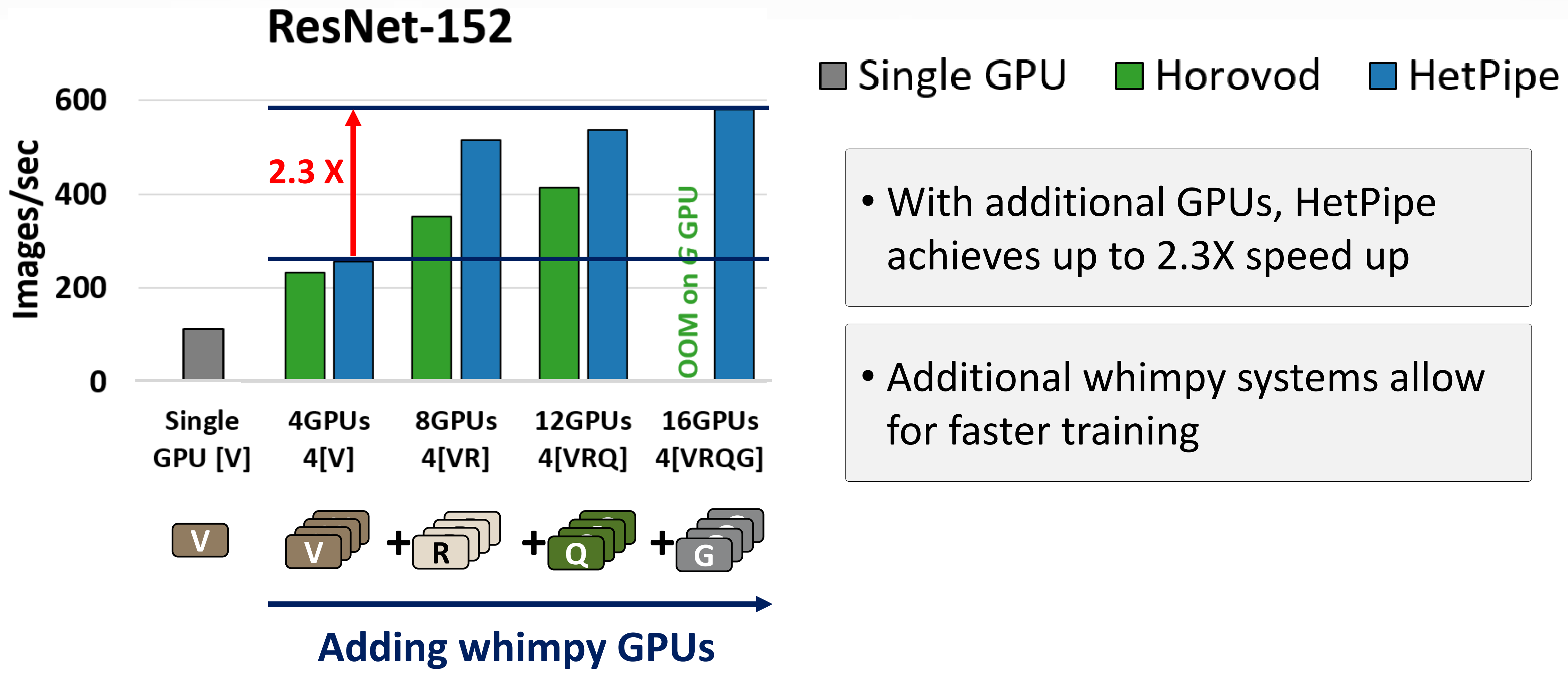
- **Baseline Horovod**
  - State-of-the-art DP using AllReduce



- For ResNet-152, the whole model is too large to be loaded into a single ***G*** type GPU (batch size = 32)

- ED: reduces the straggler problem
- ED-local: significantly reduces communication overhead

Performance Improvement of Adding Whimpy GPUs

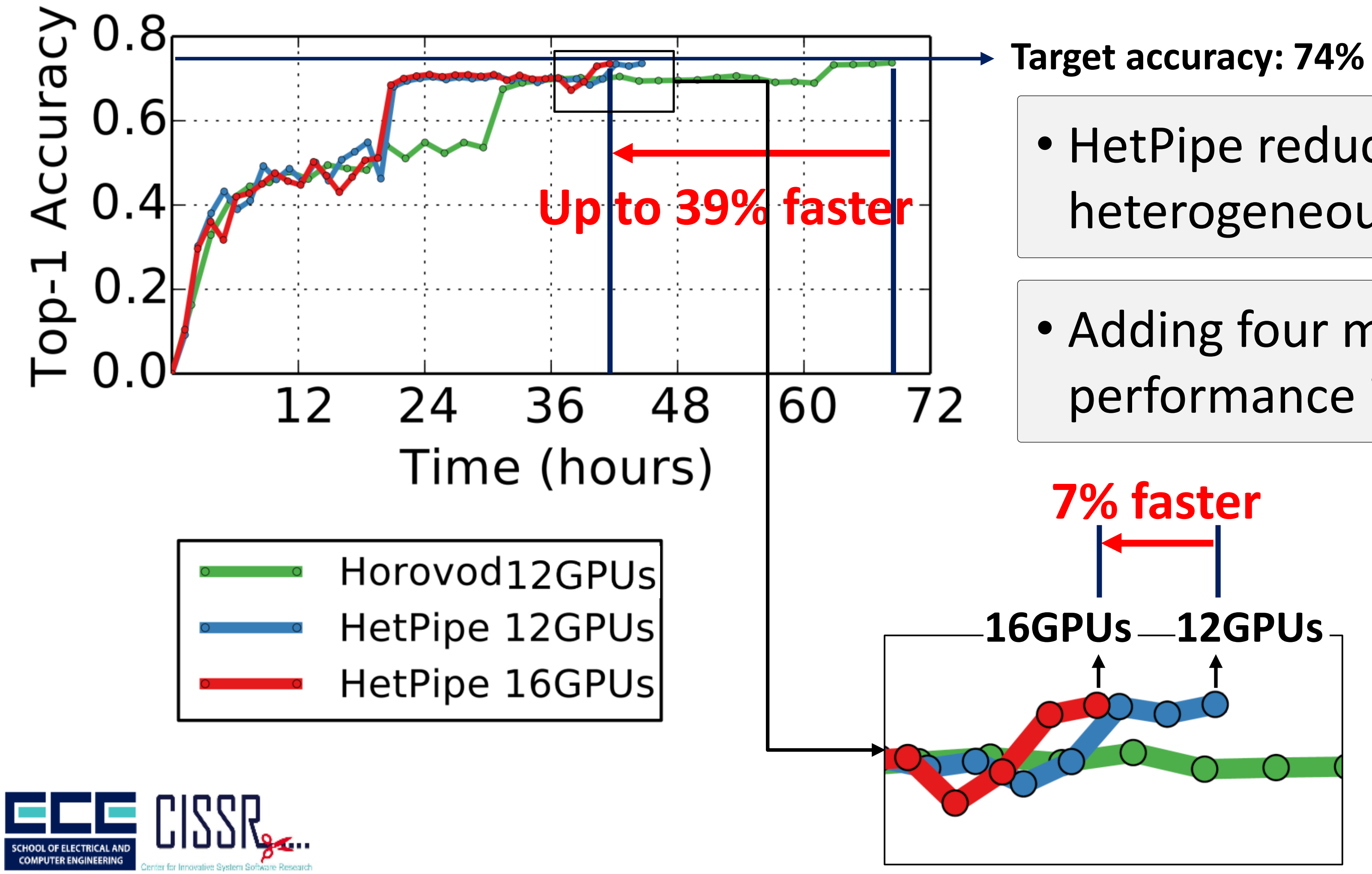


- With additional GPUs, HetPipe achieves up to 2.3X speed up

- Additional whimpy systems allow for faster training

Convergence Results

- **ResNet-152**

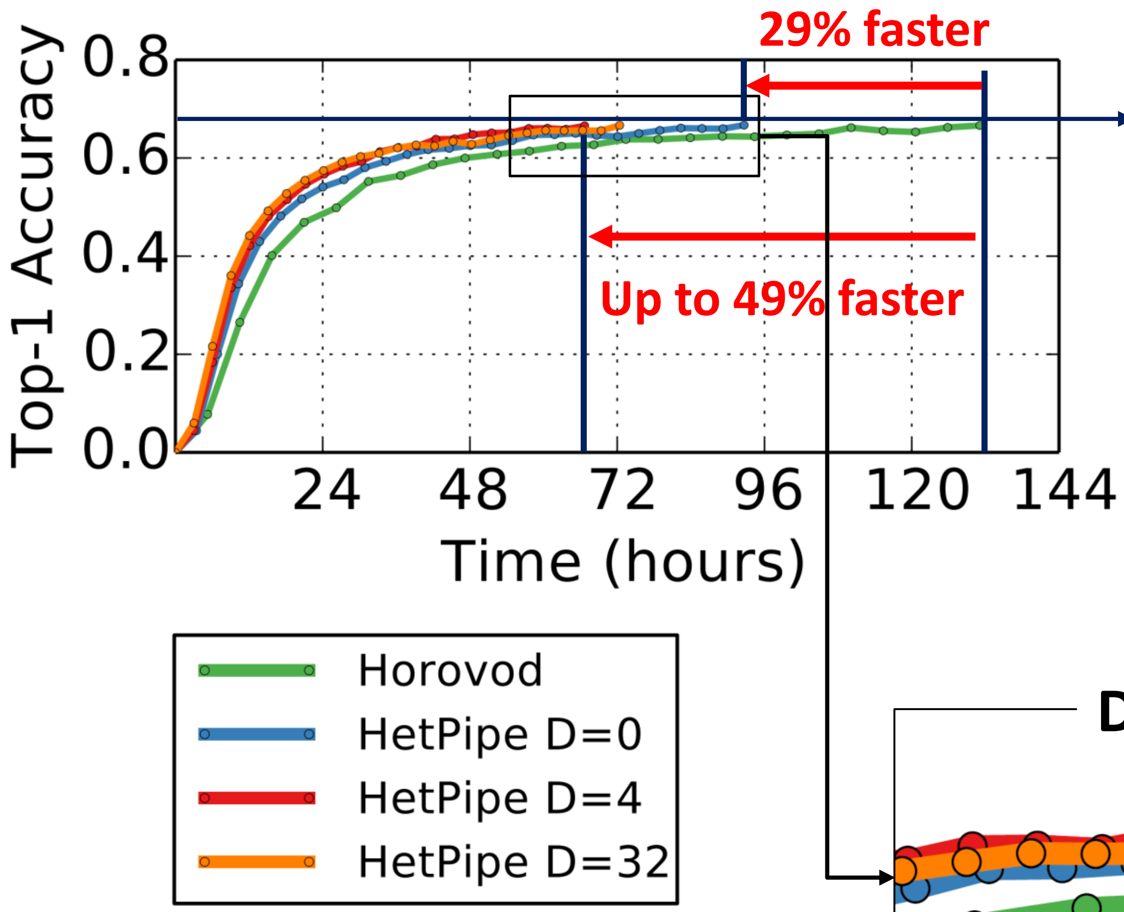


- HetPipe reduces straggler problem in heterogeneous environment

- Adding four more whimpy *G* GPUs, performance improves even more

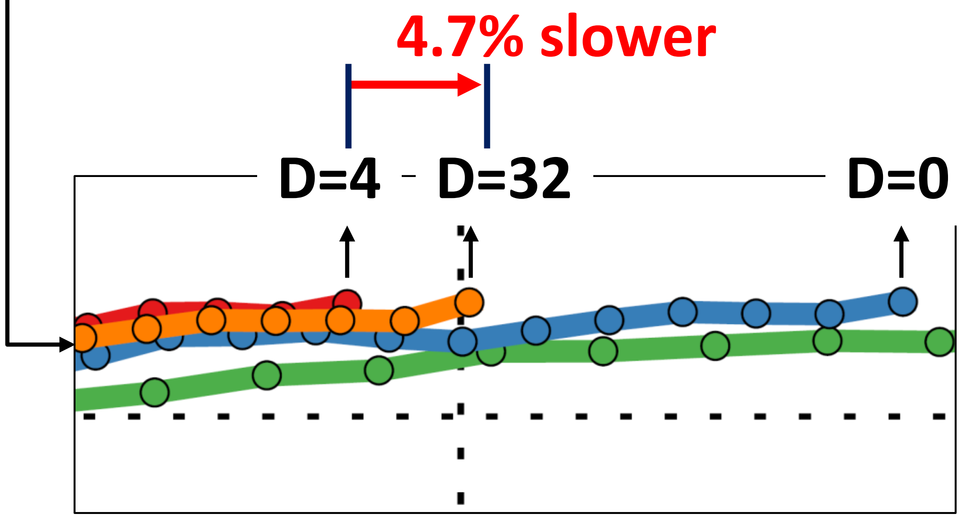
Convergence Results

- **VGG-19**



- HetPipe (D=0) is 29% faster than Horovod

- Higher global staleness (i.e., 32) can degrade convergence performance



Not Presented But Discussed in Paper

- Provide convergence proof of WSP
- Partitioning algorithm
- Performance of a single virtual worker
- Comparison to PipeDream

Conclusion

- HetPipe makes it possible to efficiently **train large DNN models with heterogeneous GPUs**
- **Integrate pipelined model parallelism with data parallelism**
- Propose a novel parameter synchronization model: **WSP**
- DNN models converge up to **49% faster with HetPipe**

Thank you!