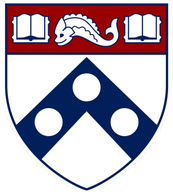
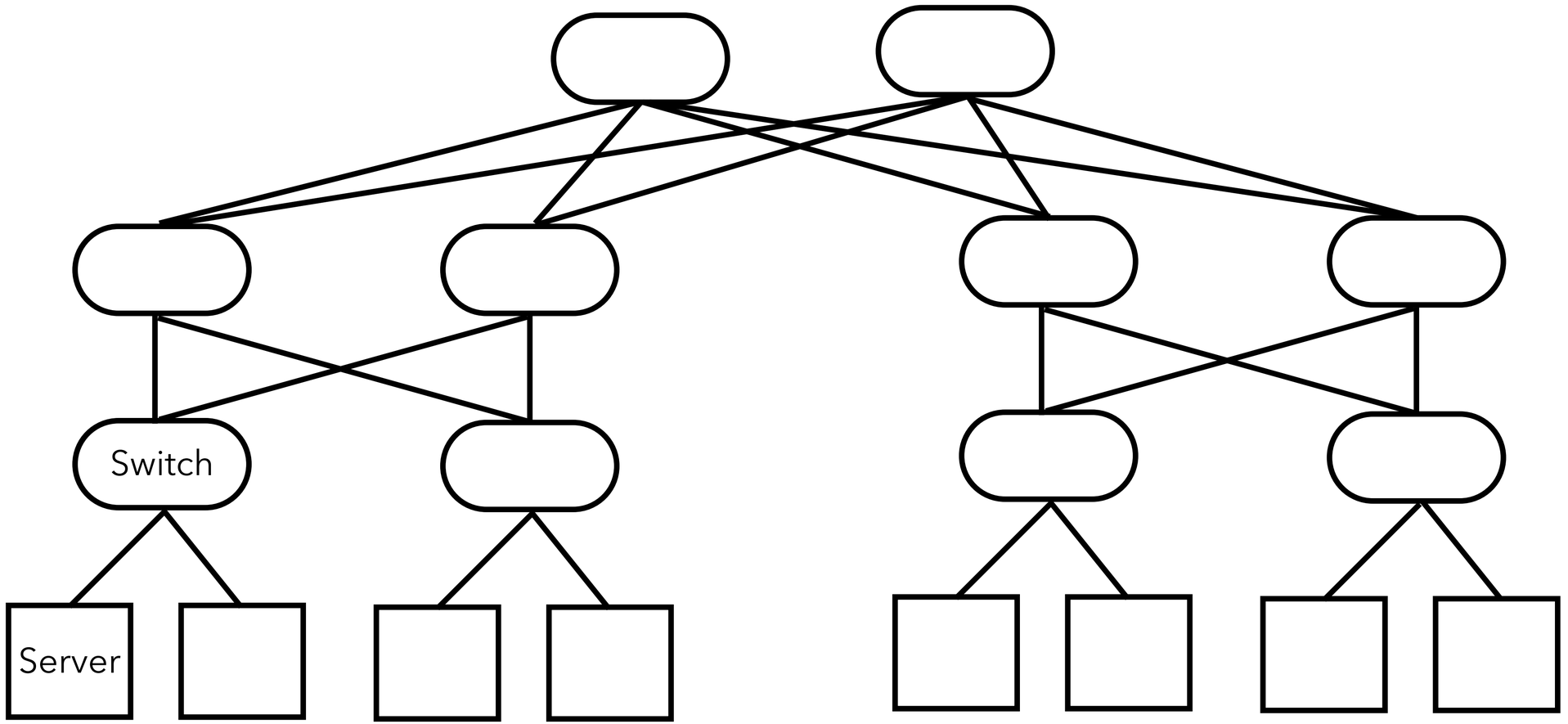
nsdi '26

FAST: An Efficient Scheduler for All-to-All GPU Communication

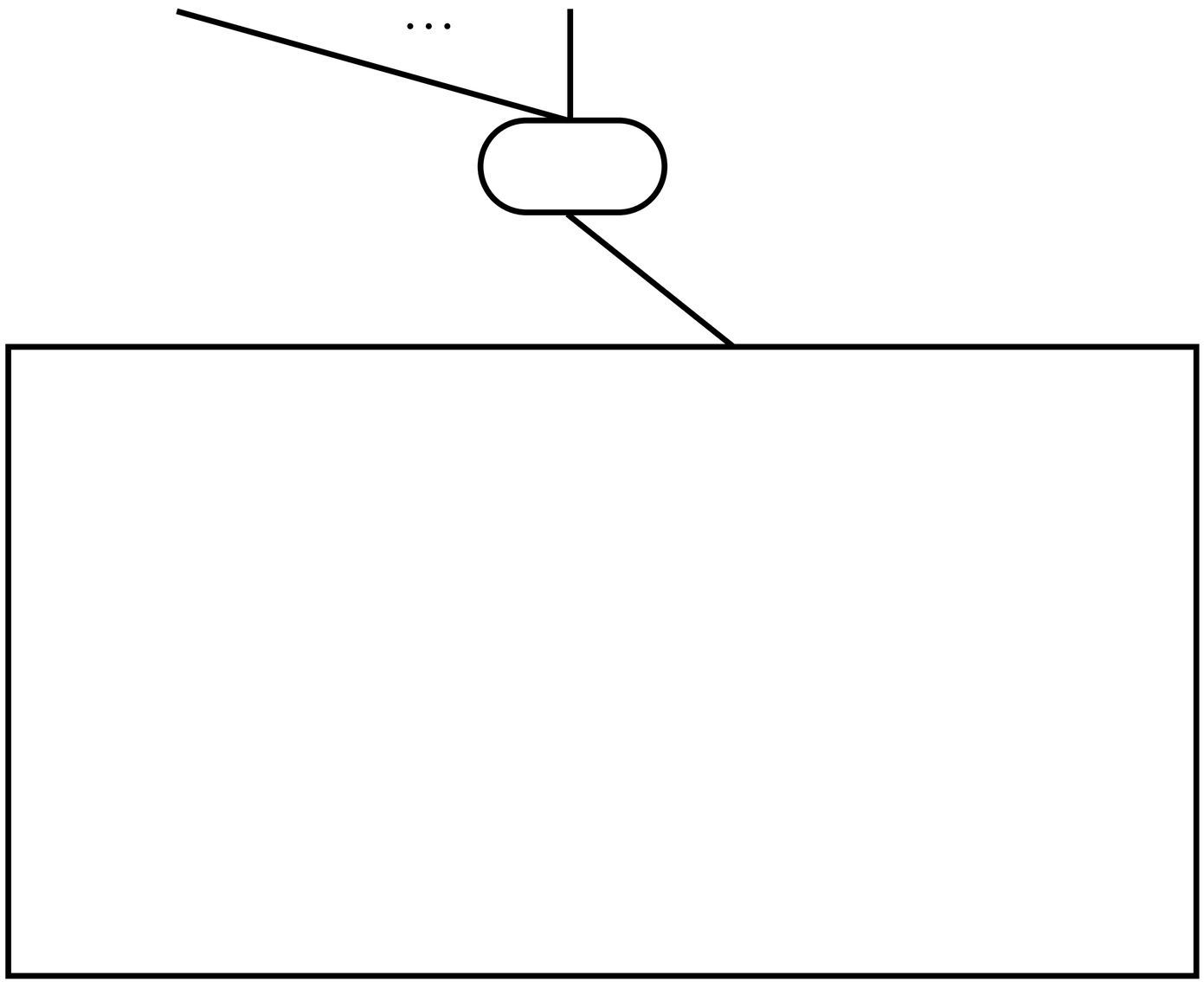
Yiran Lei, Dongjoo Lee, Liangyu Zhao, Daniar Kurniawan, Chanmyeong Kim, Heetaek Jeong, Changsu Kim, Hyeonseong Choi, Liangcheng Yu, Arvind Krishnamurthy, Justine Sherry, Eriko Nurvitadhi



Traditional data center networks



Networks inside networks



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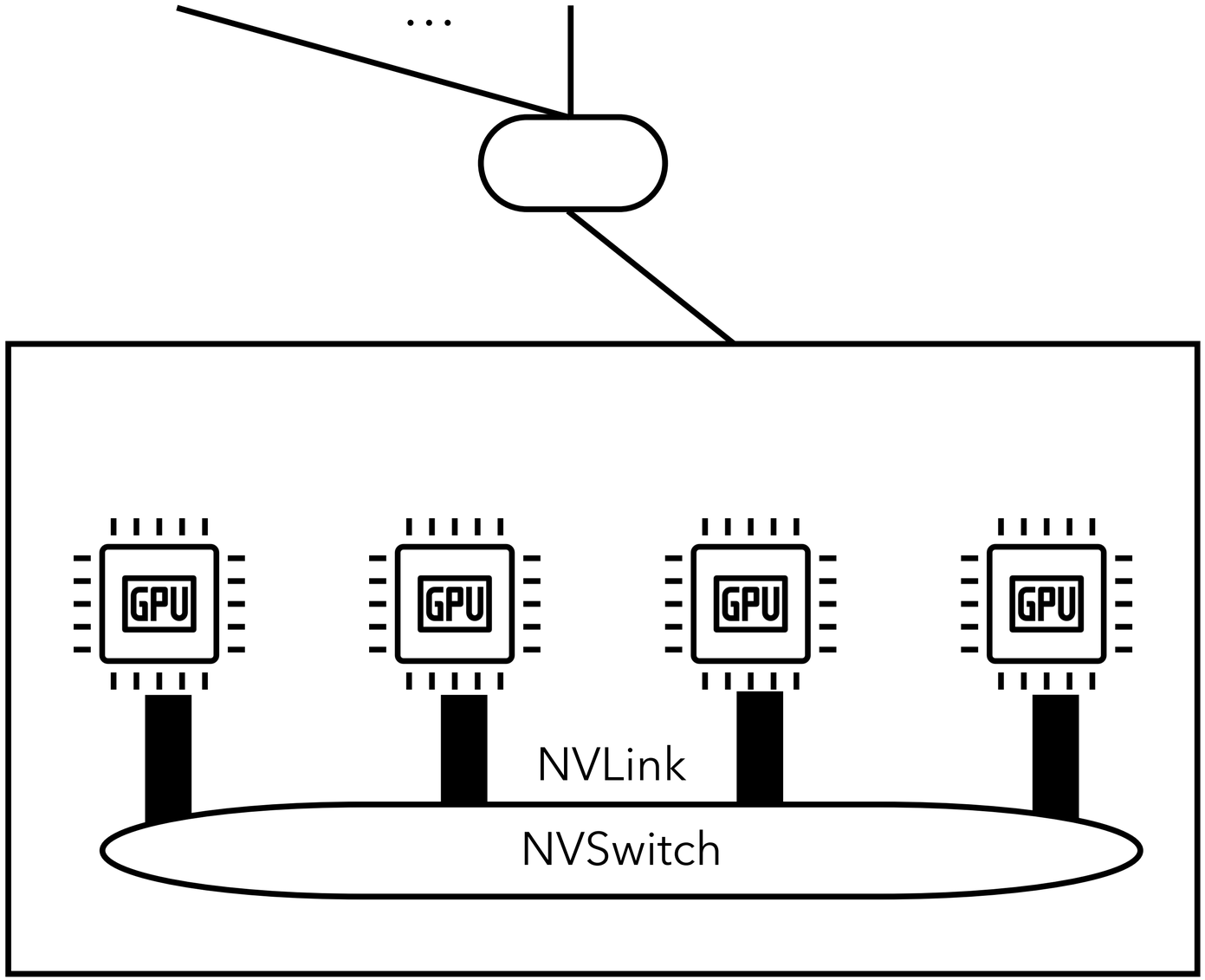

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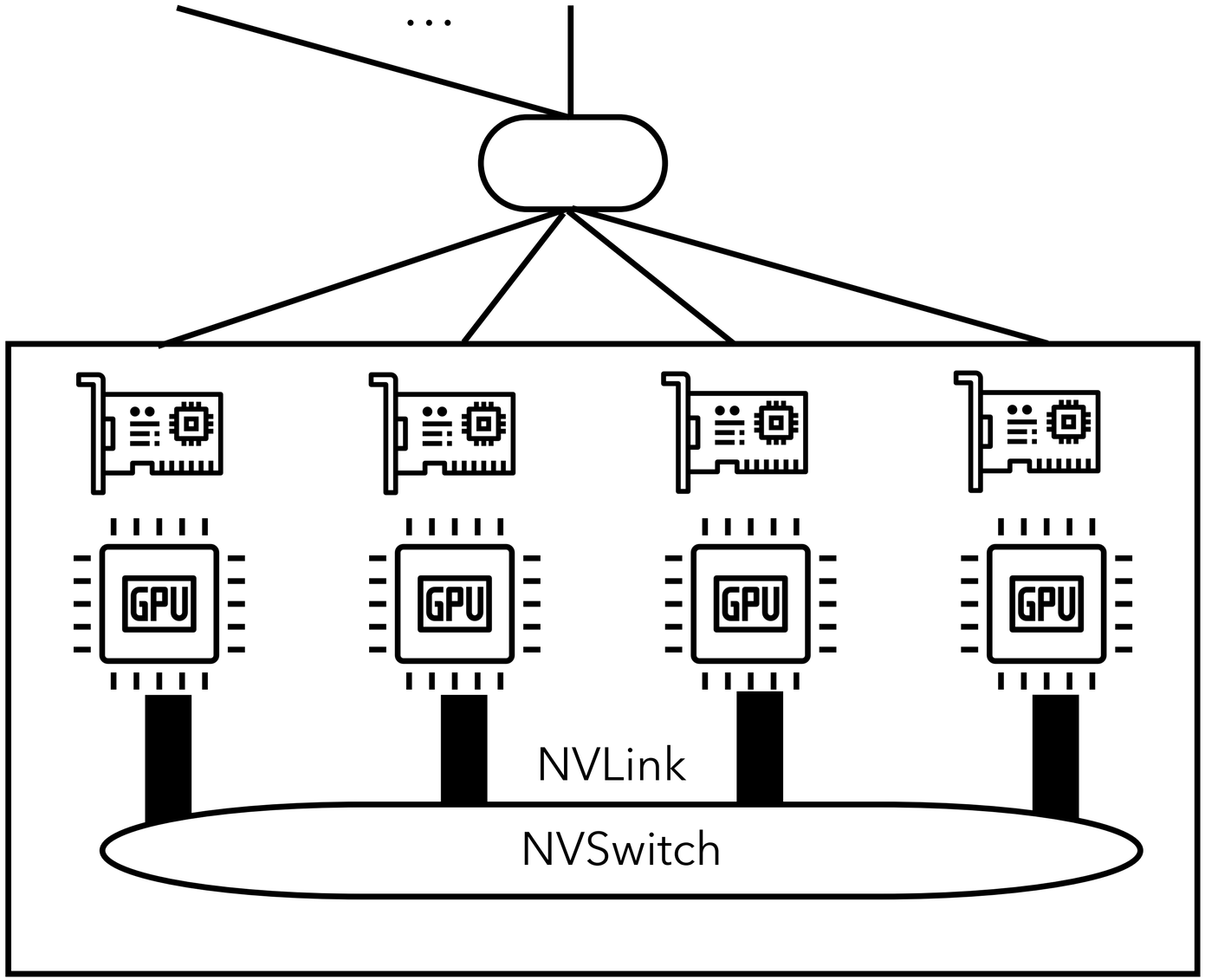

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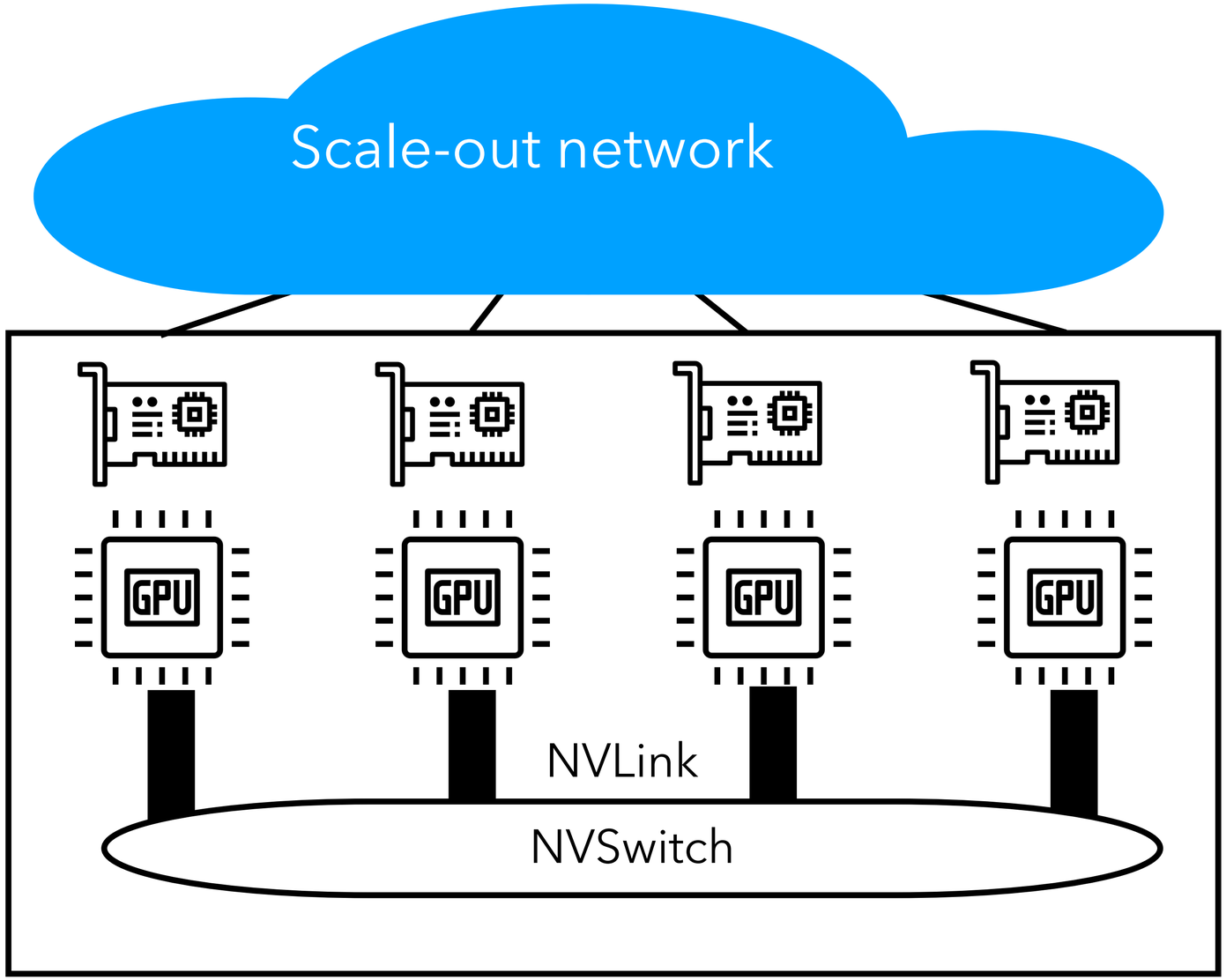

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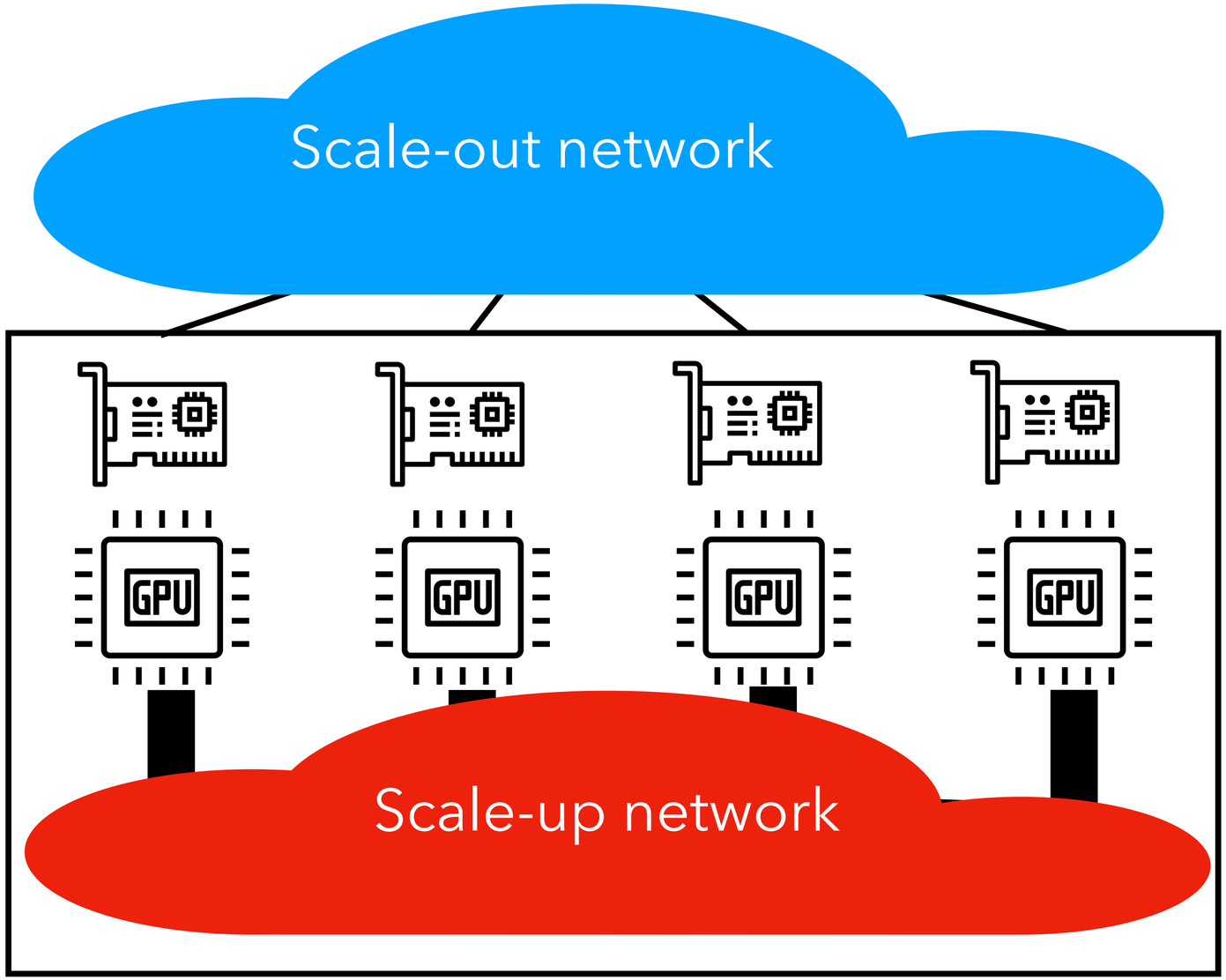
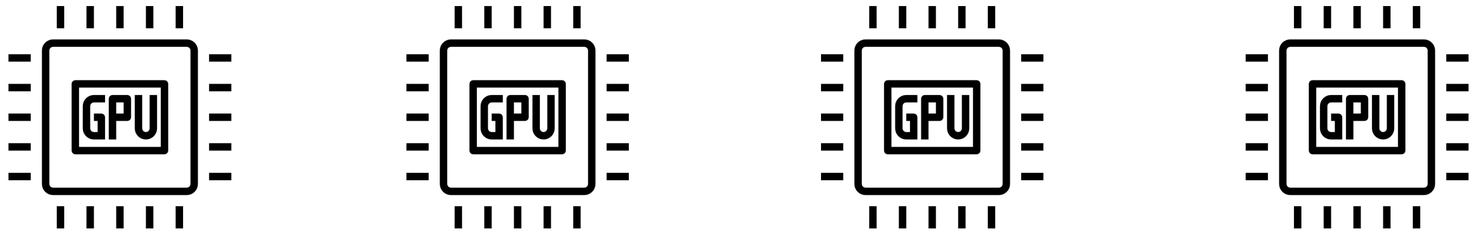


All-to-All arises on top of these networks



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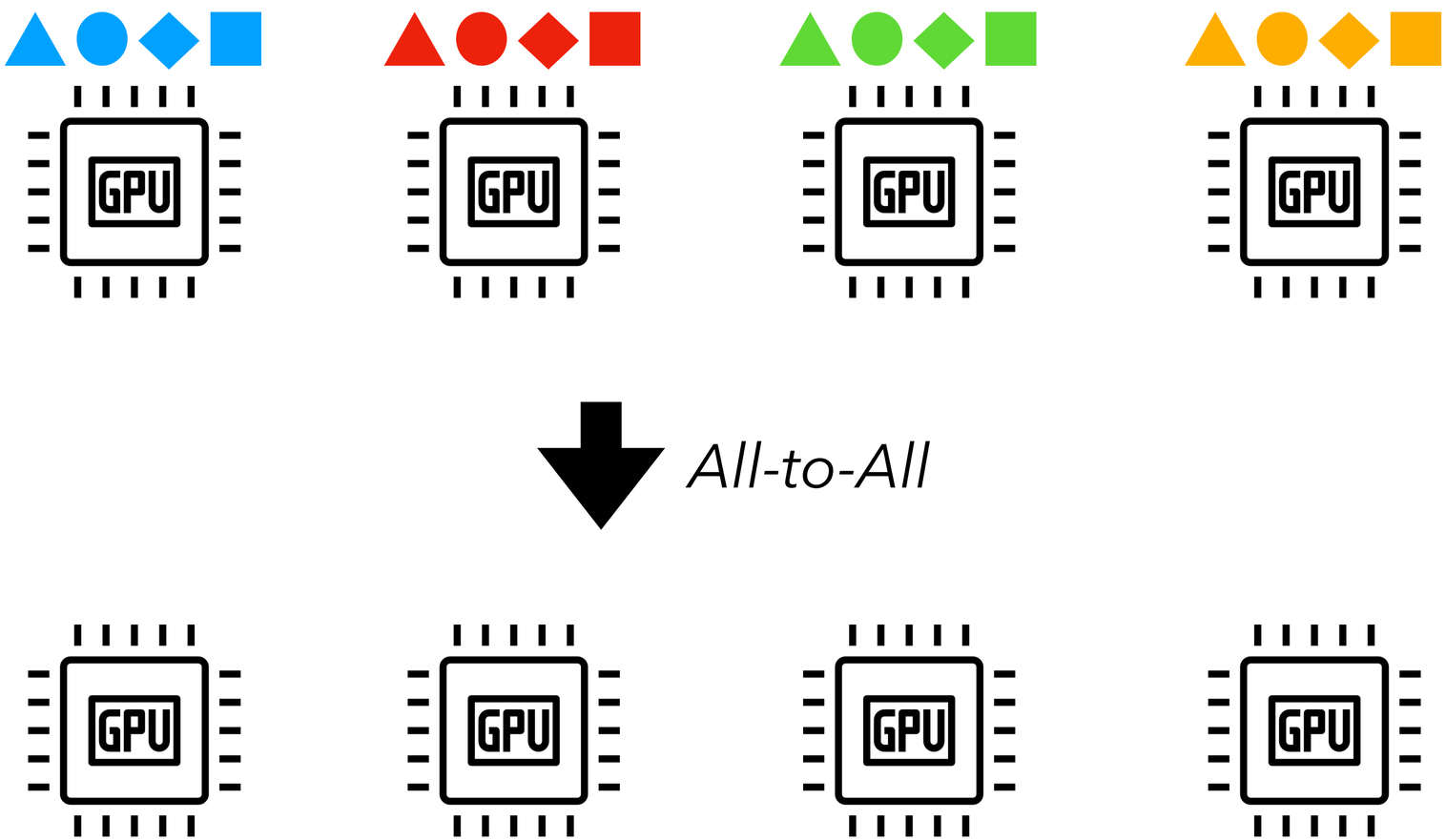

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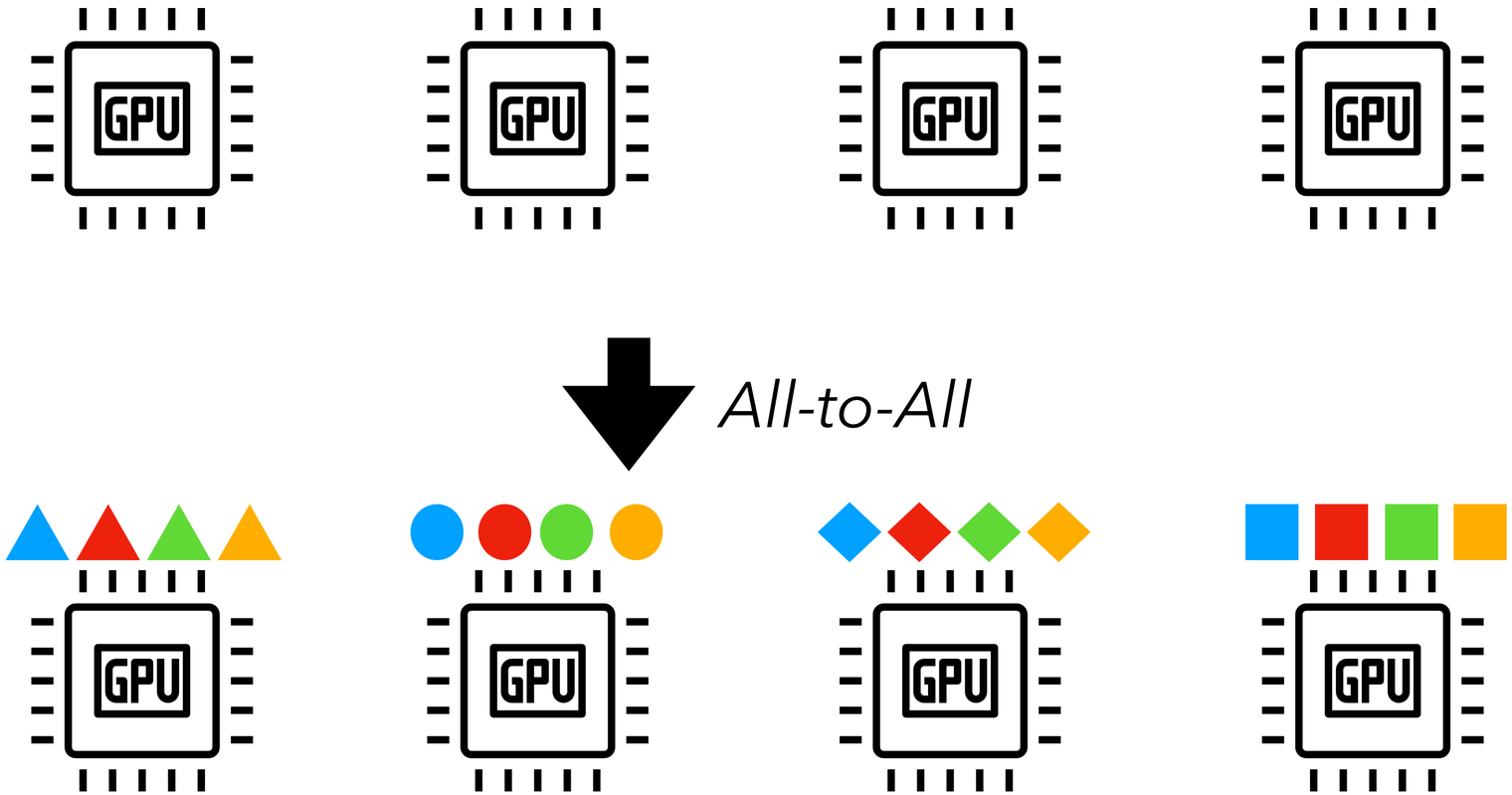


GPU1
GPU0
GPU2

All-to-All is expensive in many systems

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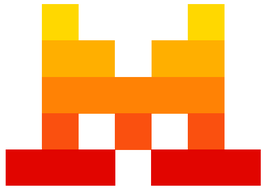
Mixture-of-Expert

DeepSeek



Mixtral

30 - 56%
of training time

All-to-All is expensive in many systems

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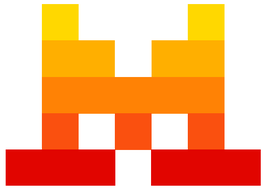

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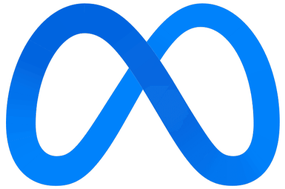

Recommendation models in Meta

55 - 82%
of total collectives

All-to-All is expensive in many systems

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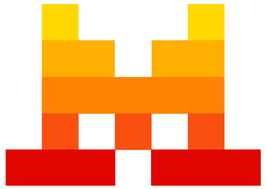

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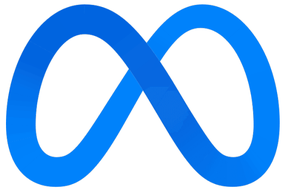

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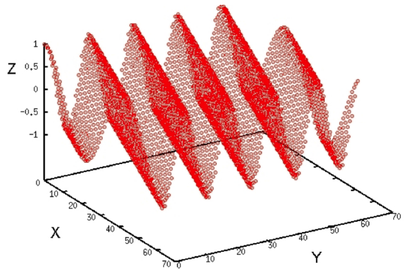
HPC workloads



3D FFT

Up to 97.3%
of runtime

All-to-All is expensive in many systems

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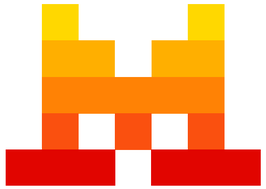

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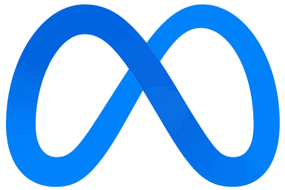

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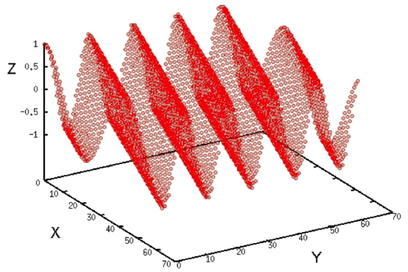

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We need efficient All-to-All!

Two costs: moving data and planning move

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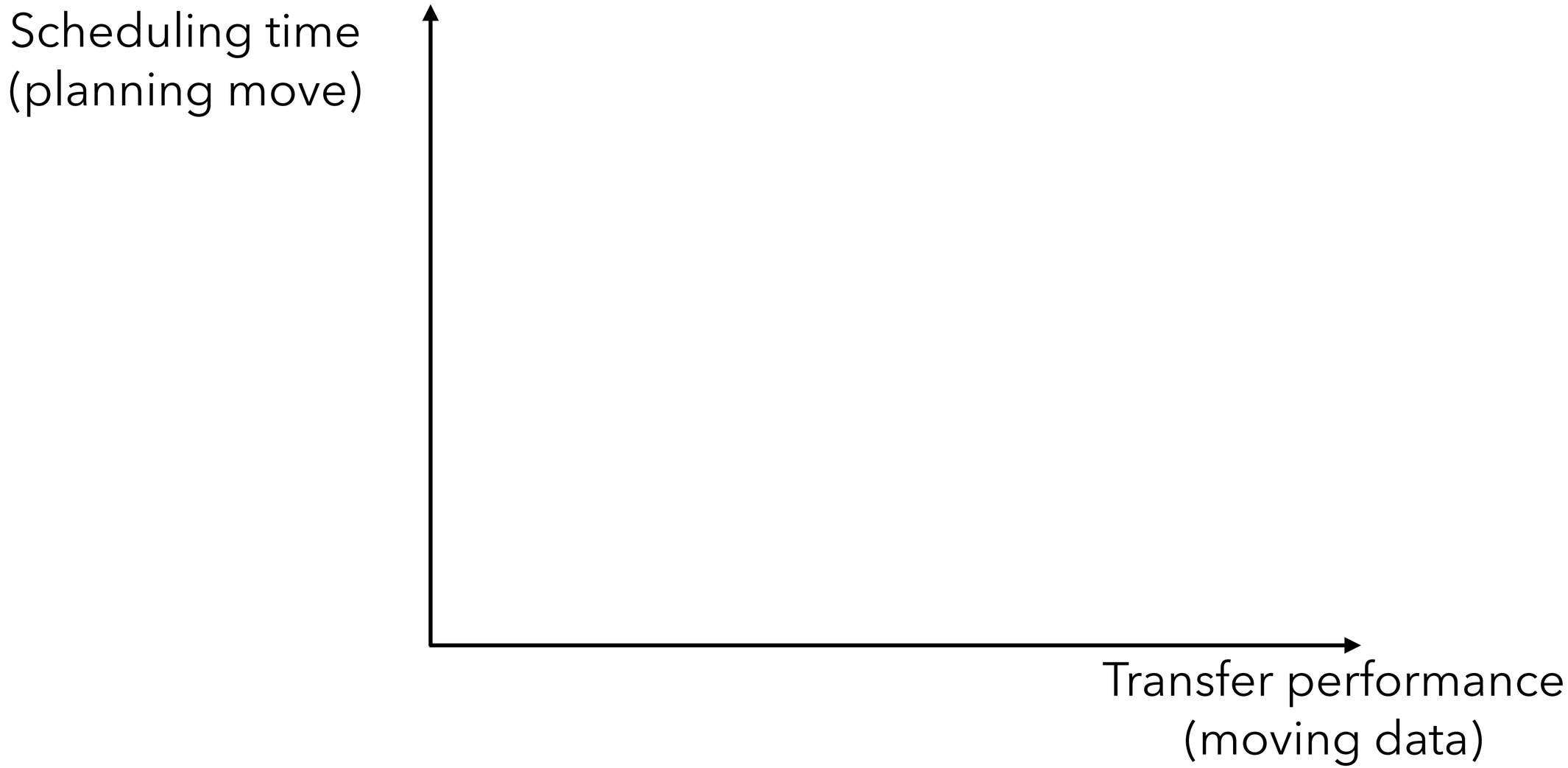
Transfer performance
(moving data)

Two costs: moving data and planning move



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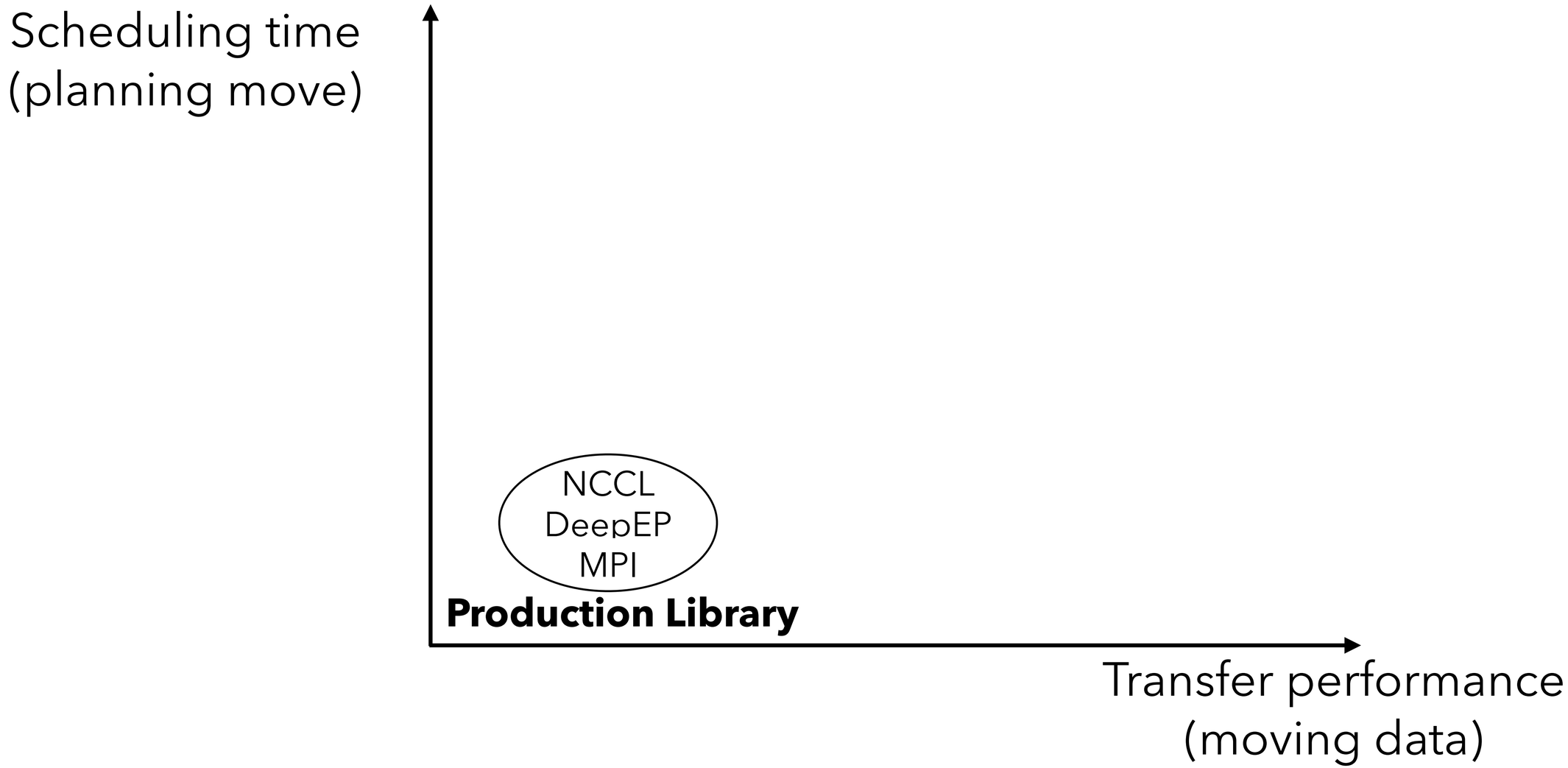

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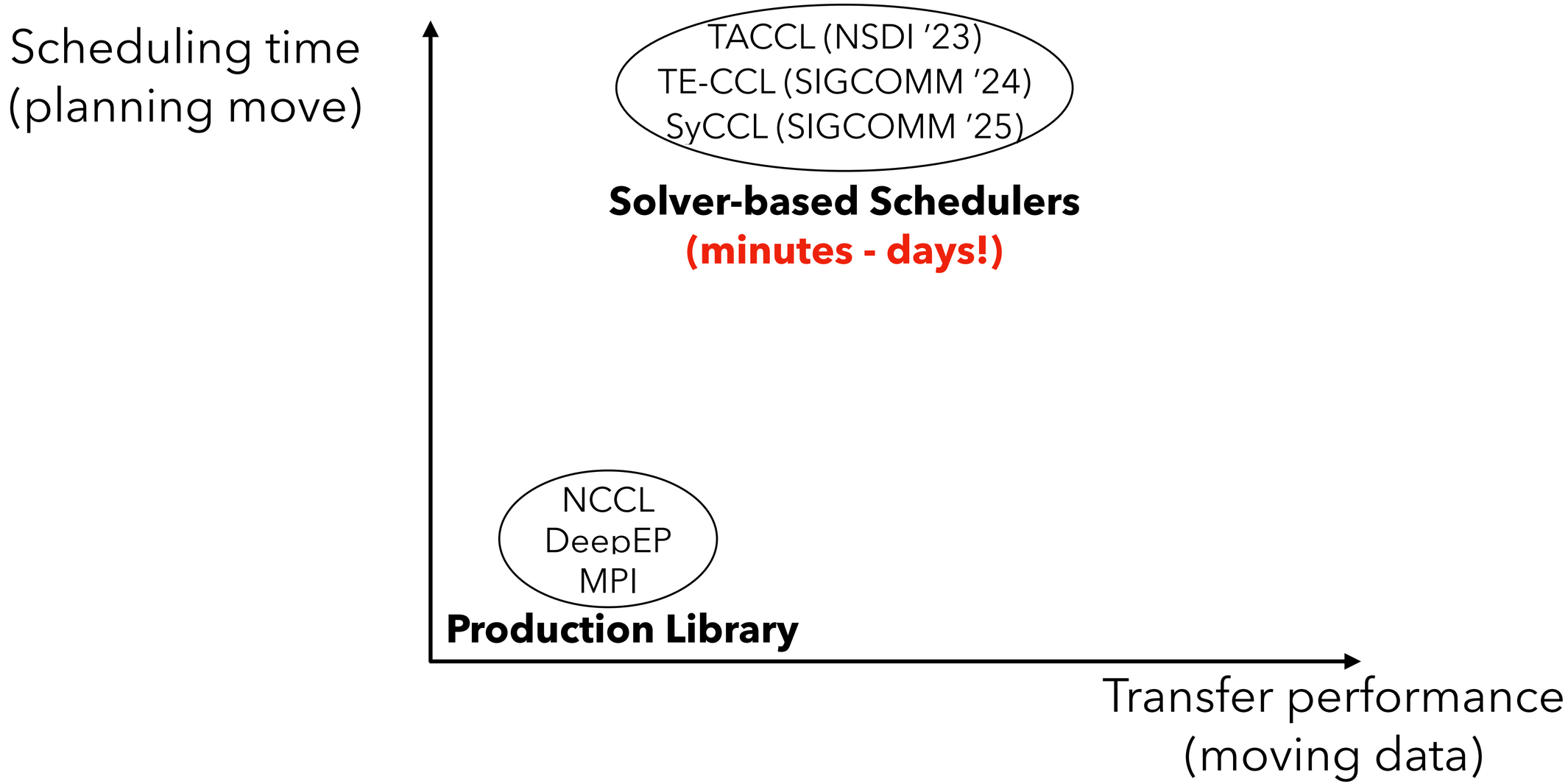


Two costs: moving data and planning move

Scheduling time
(planning move)

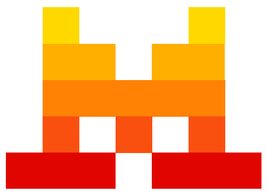
TACCL (NSDI '23)
TE-CCL (SIGCOMM '24)
SyCCL (SIGCOMM '25)

Solver-based Schedulers
(minutes - days!)

NCCL
DeepEP
MPI

Production Library

Transfer performance
(moving data)



In MoE, skewed traffic,
refreshed every few 100 ms

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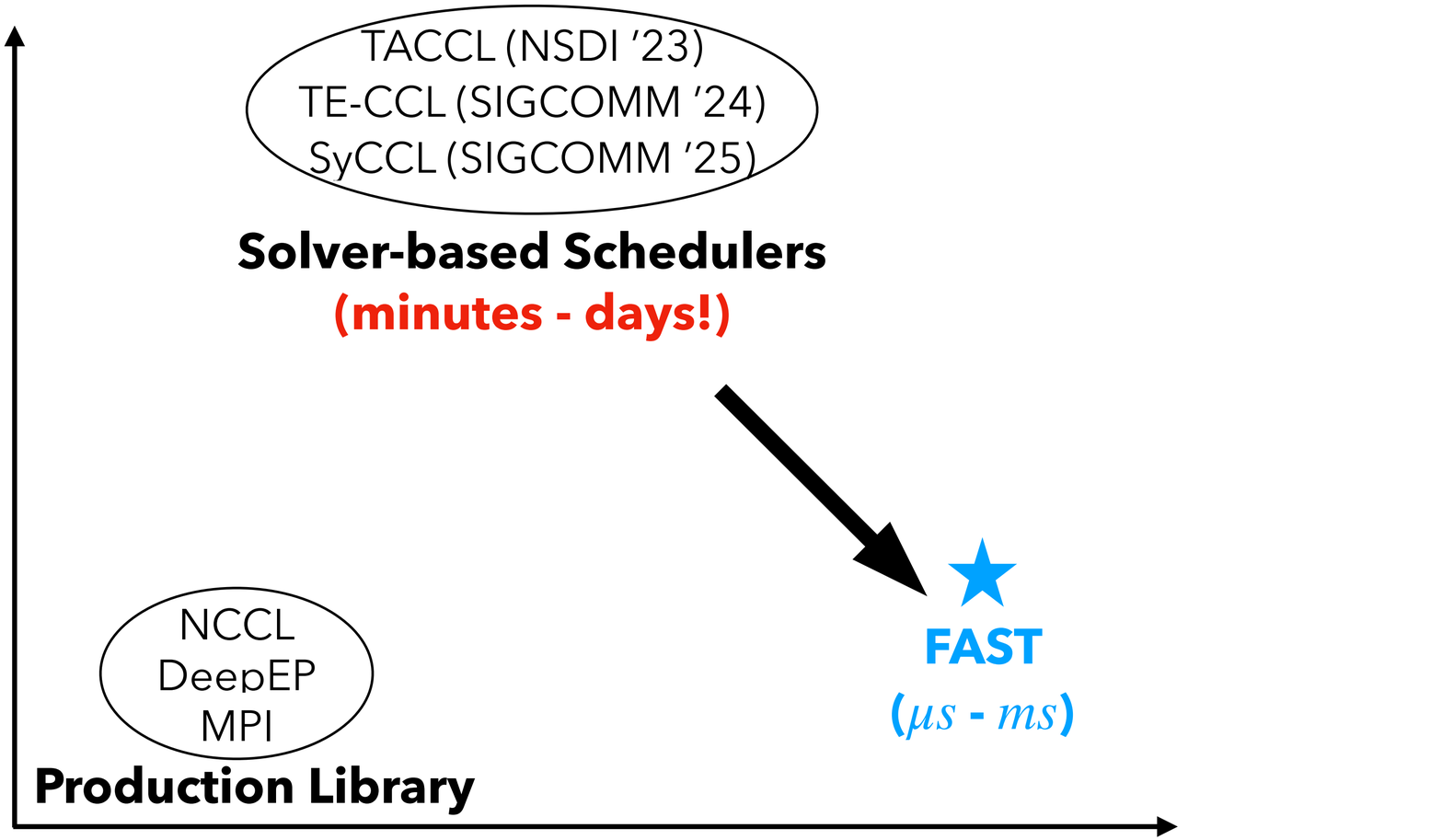

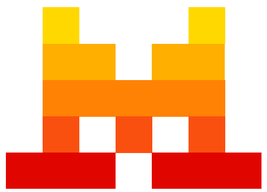

In MoE, skewed traffic,
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What is a scheduler solving?

$$\text{Minimize} \quad time \tag{1}$$

$$time \geq start[c,r] \quad \forall (c,r) \in coll.\text{postcondition} \tag{2}$$

$$start[c,r] = 0 \quad \forall (c,r) \in coll.\text{precondition} \tag{3}$$

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$$is\_sent[c,src,r] \rightarrow start[c,r] = send[c,src,r] + lat(src,r) \quad \forall c \in \mathcal{C} \quad \forall (src,r) \in \mathcal{L} \tag{5}$$

$$time \geq \sum_{c \in C} (lat(src,r) * is\_sent[c,src,r]) \quad \forall (src,r) \in \mathcal{L} \tag{6}$$

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Who sends what, to whom, through who, and when?

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NP-hard formulation

Why hard#1: last flow determines completion

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Completion = when **longest** flow finish

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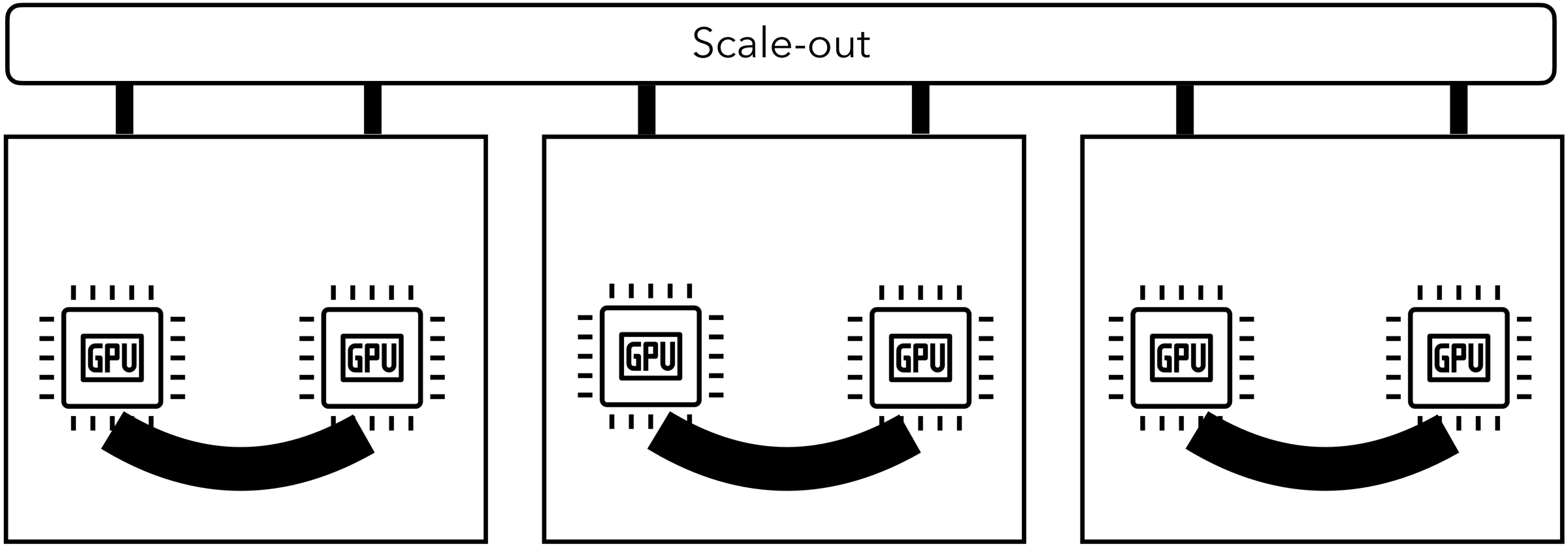
Why hard#2: incast creates stragglers



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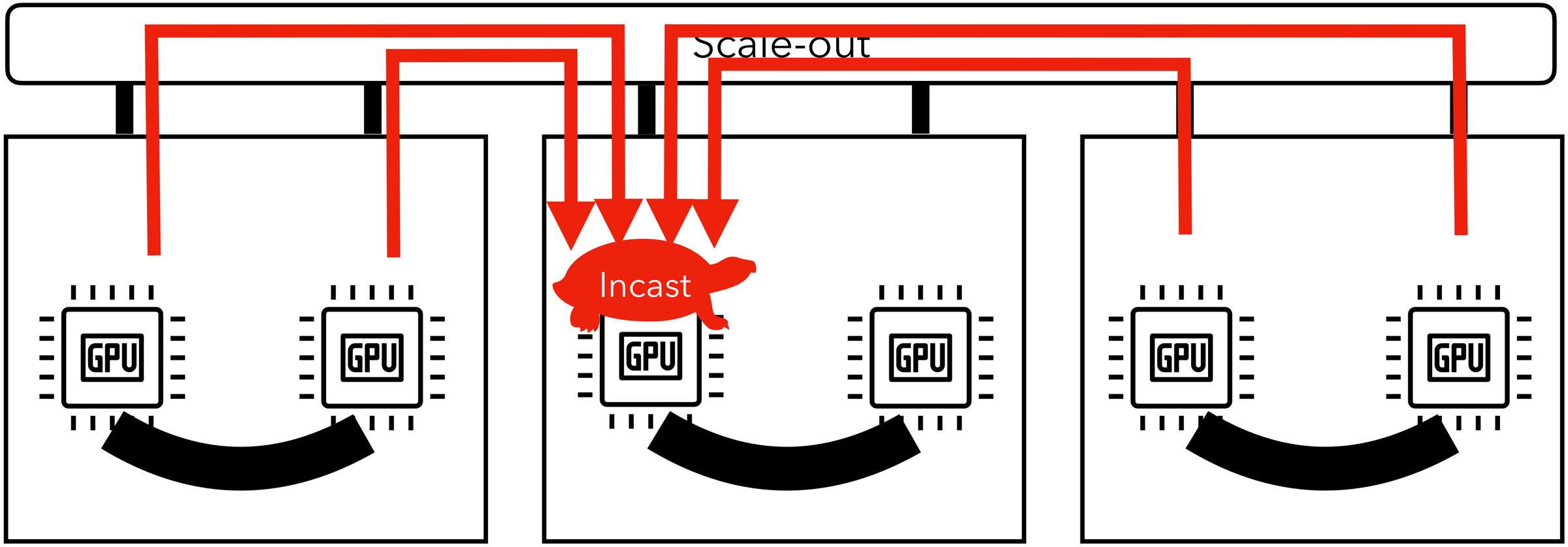

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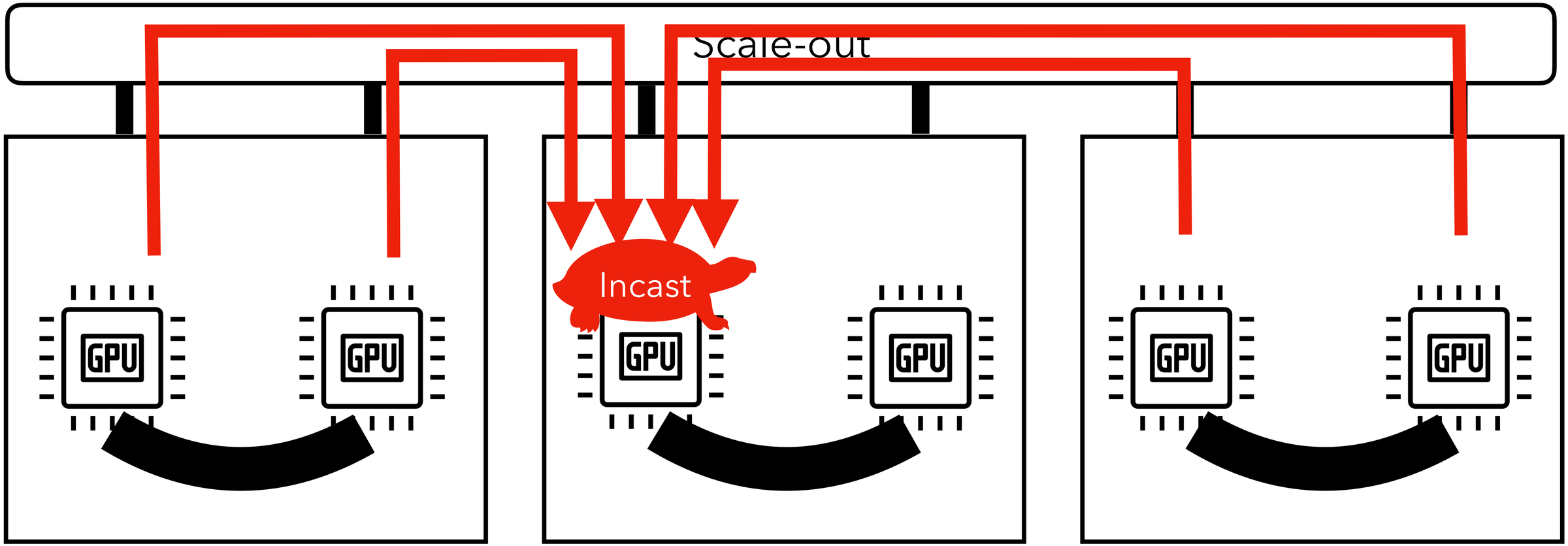

Avoid incast: **at most one flow** per sender, per receiver

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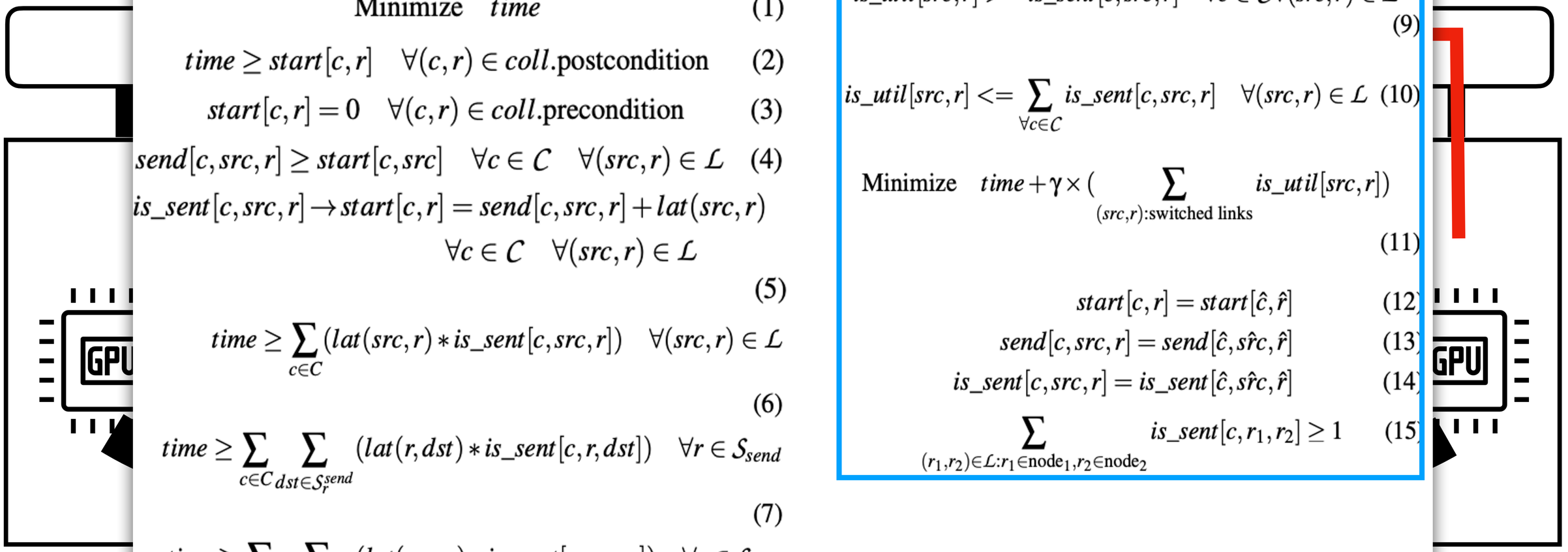

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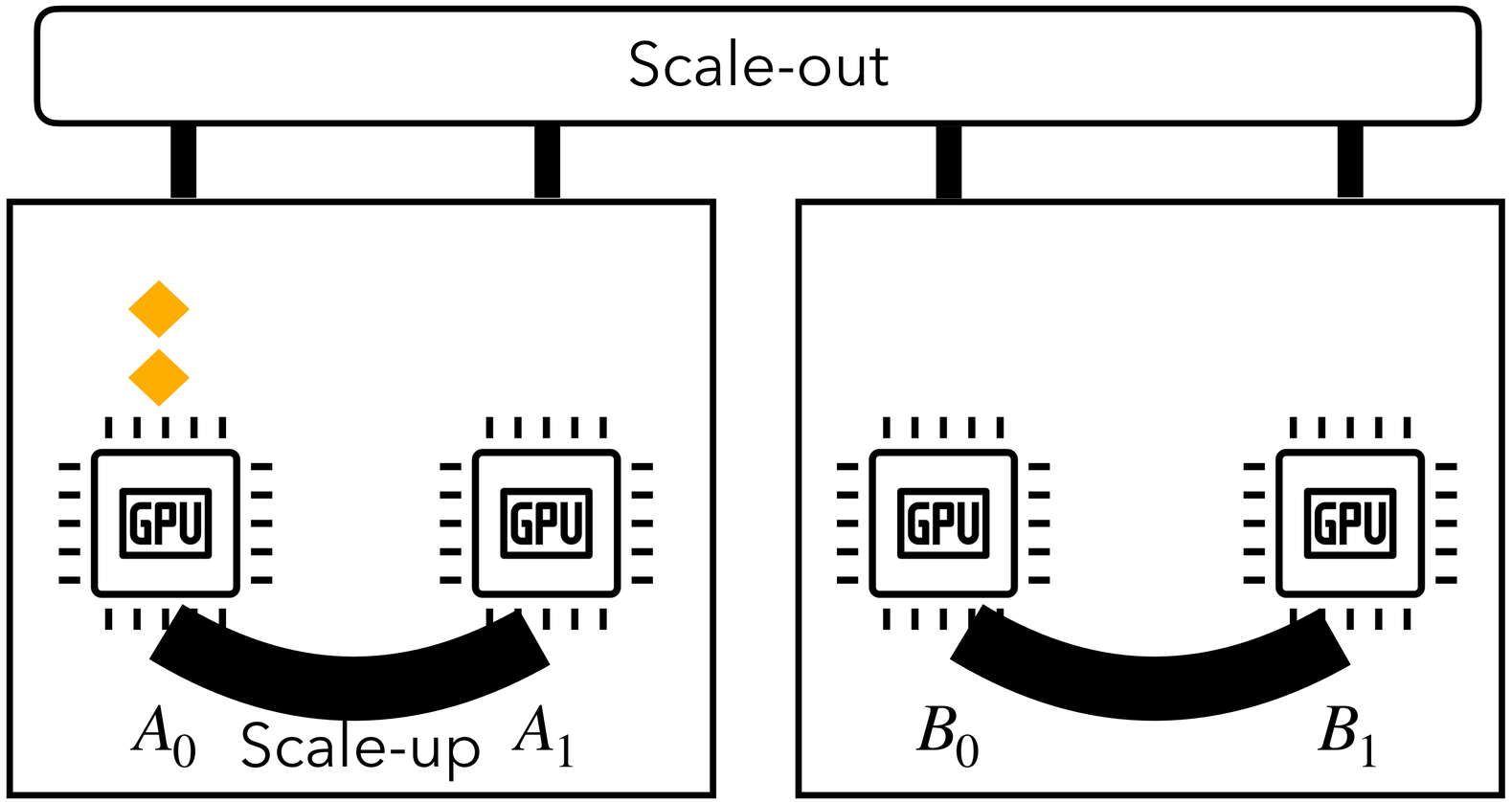
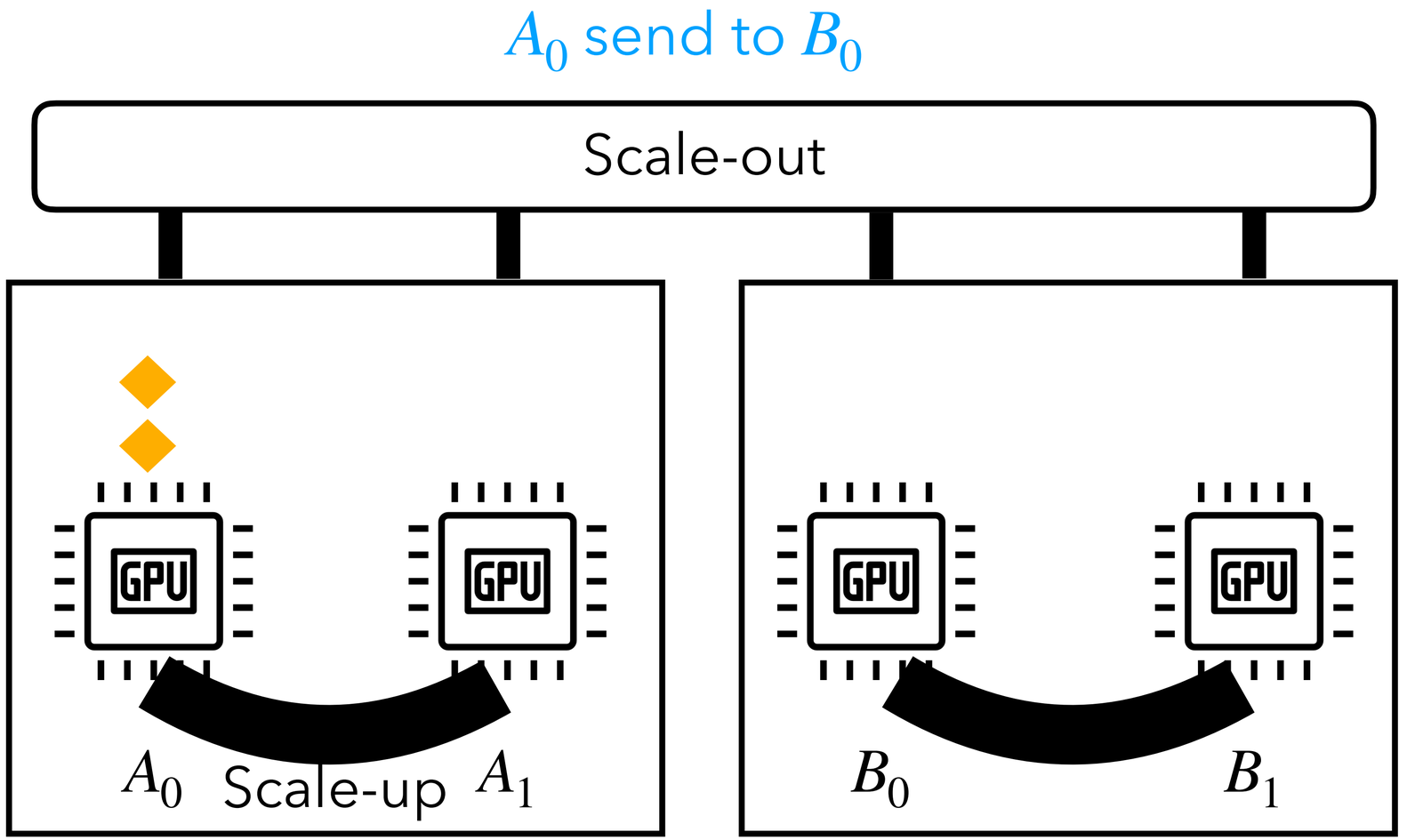
$$\sum_{(r_1,r_2) \in \mathcal{L}: r_1 \in \text{node}_1, r_2 \in \text{node}_2} is\_sent[c,r_1,r_2] \geq 1 \tag{15}$$

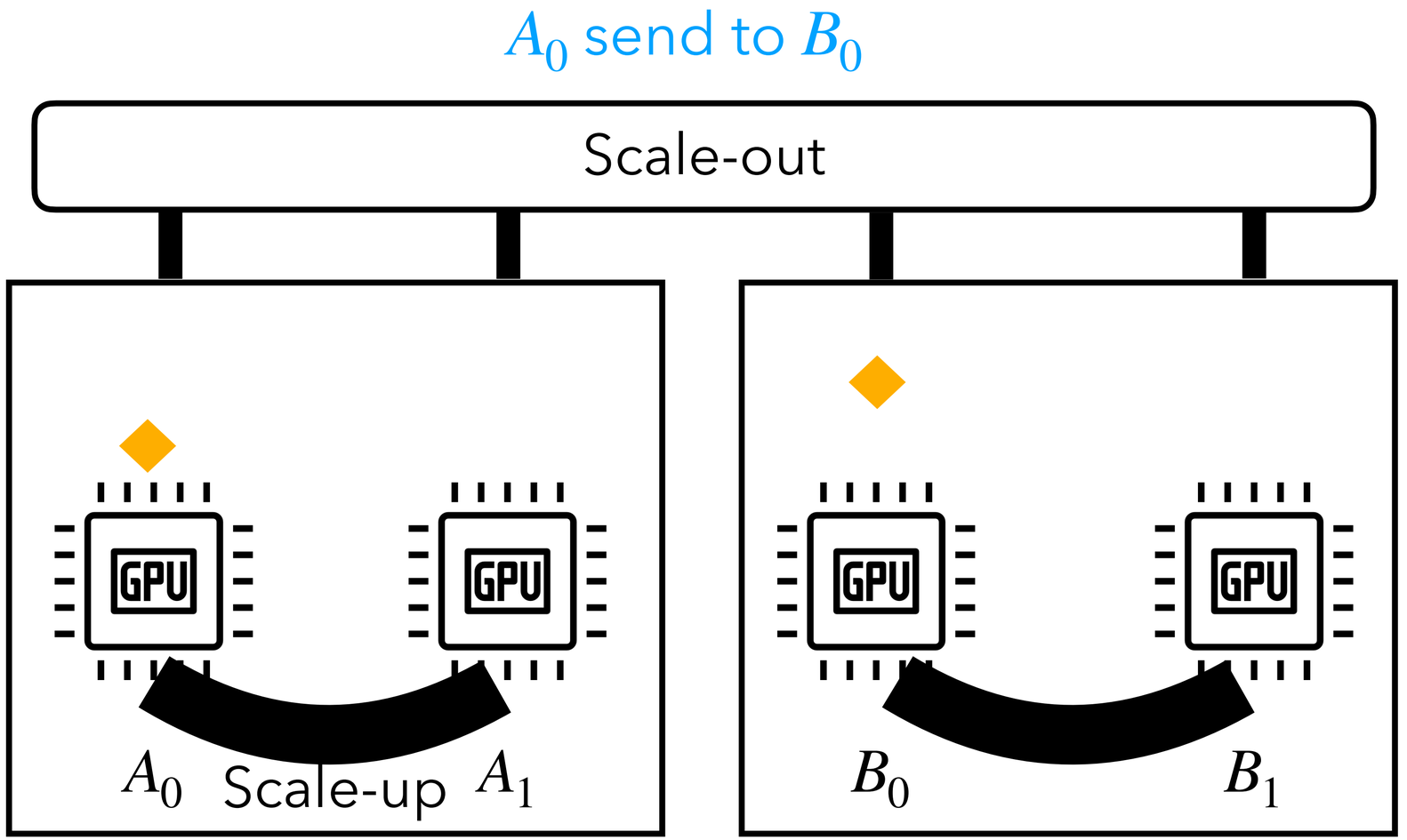
Why hard#3: waypointing explodes the decision space



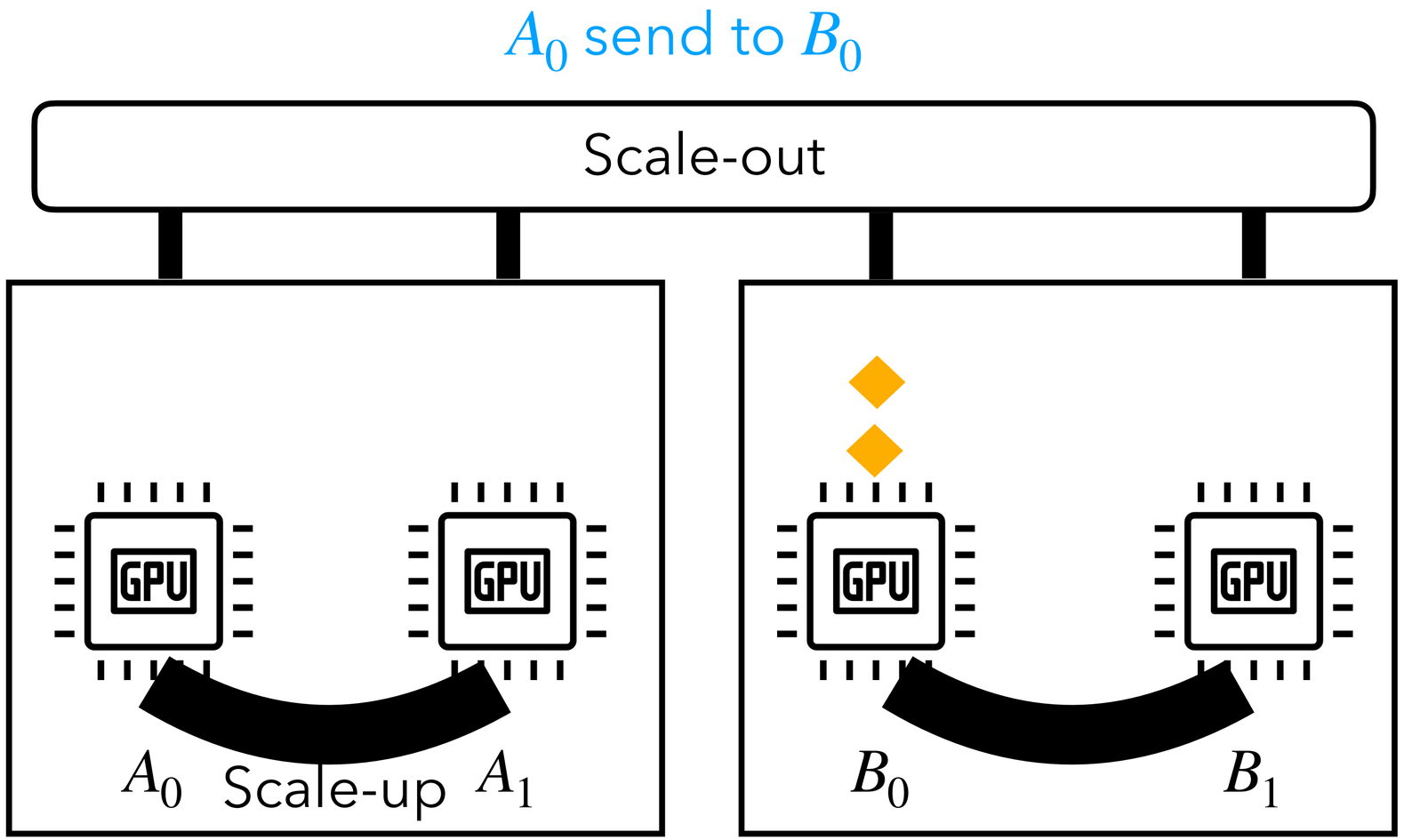
Why hard#3: waypointing explodes the decision space



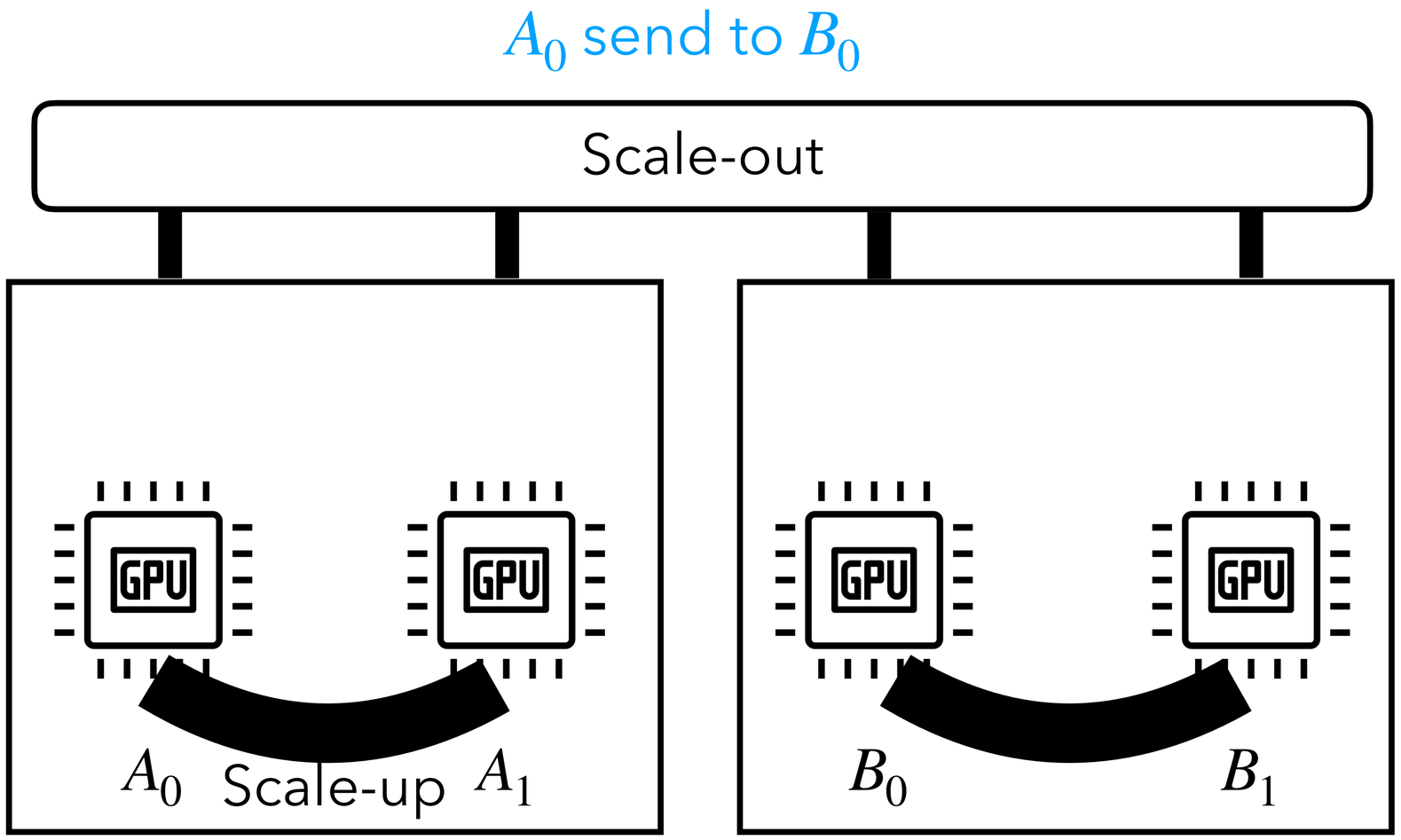
Why hard#3: waypointing explodes the decision space



Why hard#3: waypointing explodes the decision space

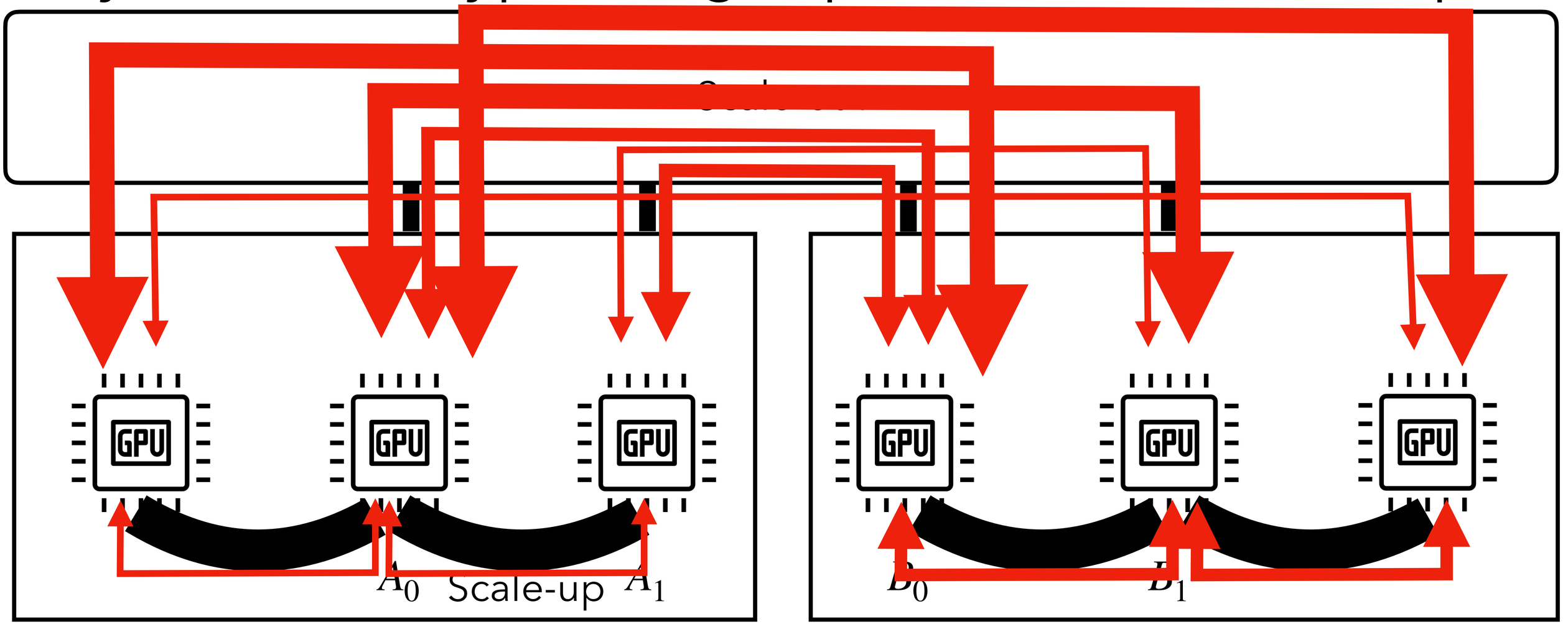


Why hard#3: waypointing explodes the decision space



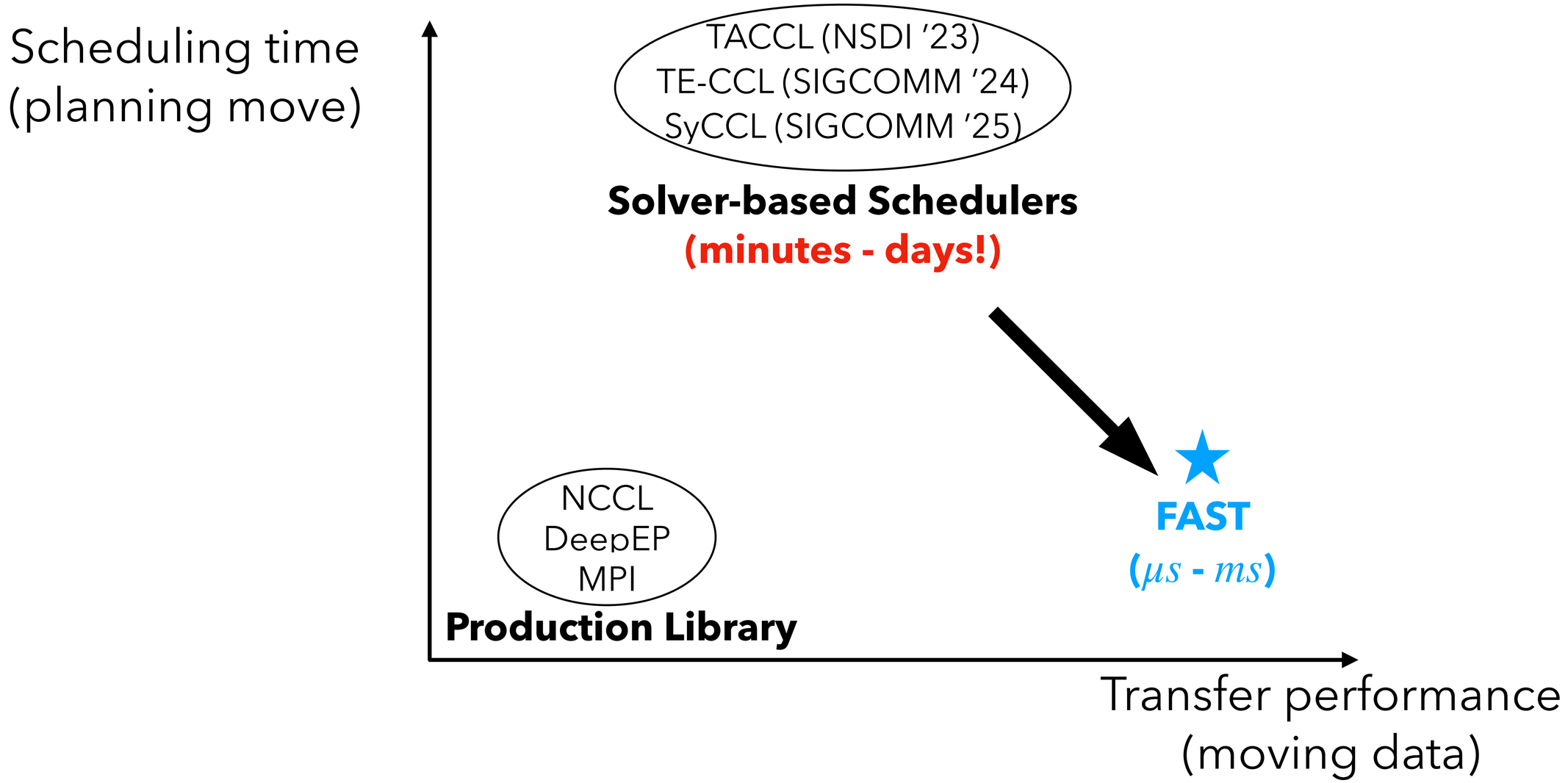
$$2 \times \frac{\text{amount of data waypointed}}{\text{scale-up BW}} + \frac{\text{remaining data not waypointed}}{\text{scale-out BW}}$$

Why hard#3: waypointing explodes the decision space



Why hard#3: waypointing explodes the decision space

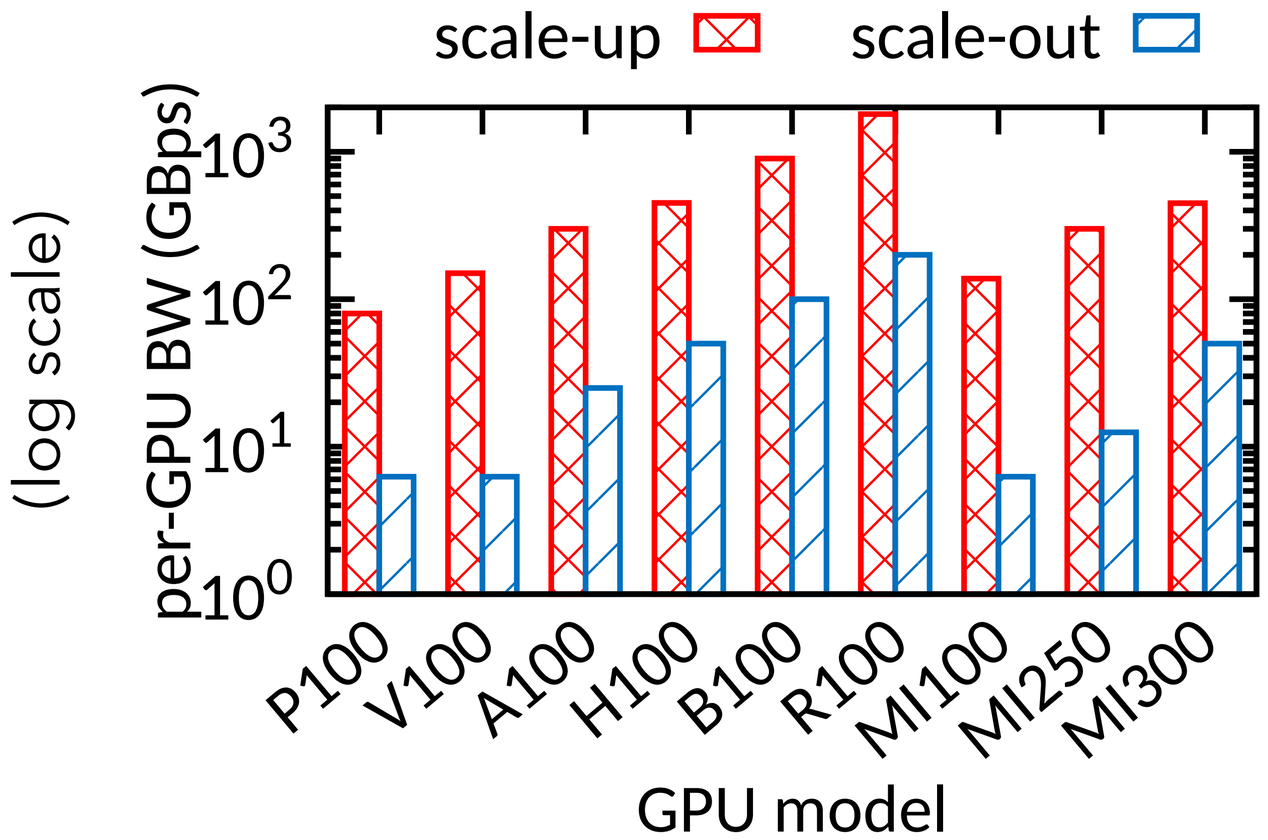
How do we get there?



Pretend scale-up is free

Scale-up is “almost free”

Scale-up bandwidth ≈ 9x scale-out



Scale-out network is bottleneck when scale-up is infinitely fast

Scale-out network is bottleneck when scale-up is infinitely fast

(Optimal scale-out schedule)

Global Scheduling

Scale-out network is bottleneck when scale-up is infinitely fast

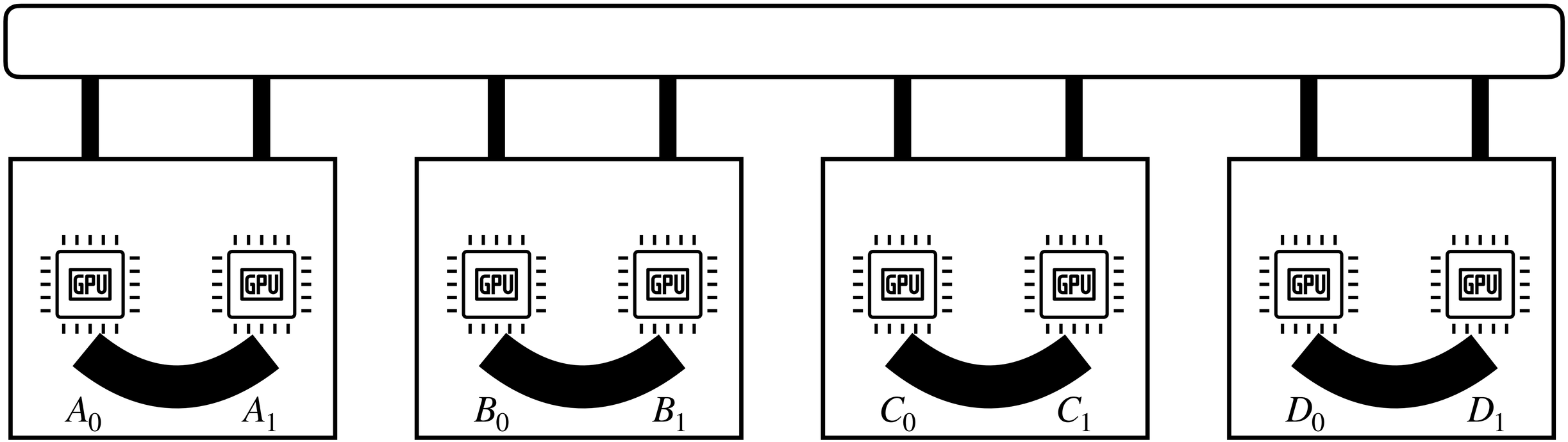
(Optimal scale-out schedule)

Global Scheduling

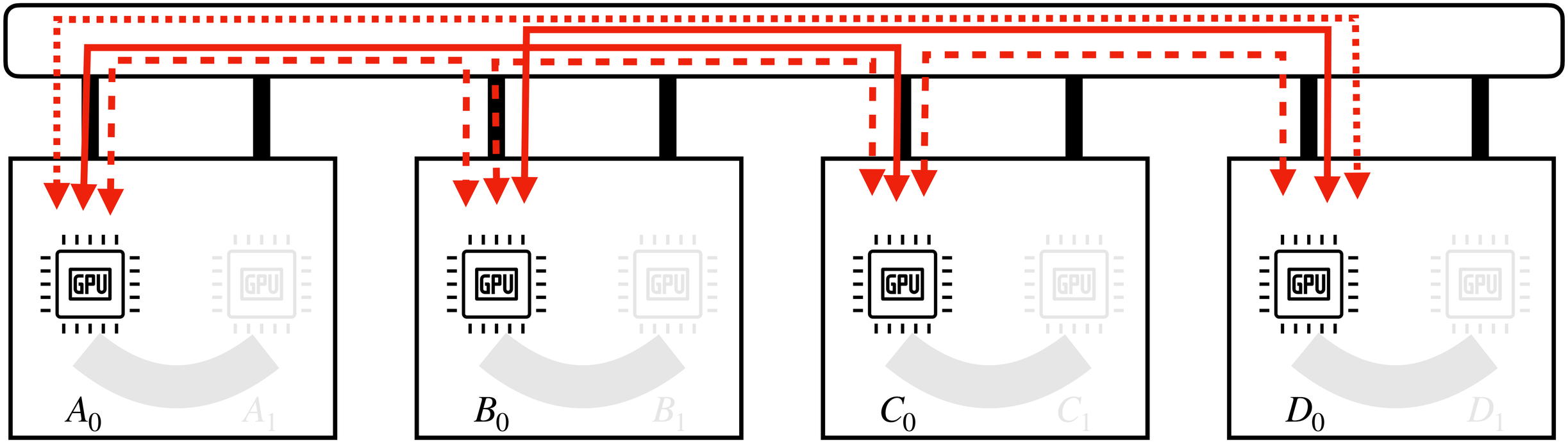
Local Scheduling

(Further speedup using scale-up)

Optimal scale-out transfers with no incast

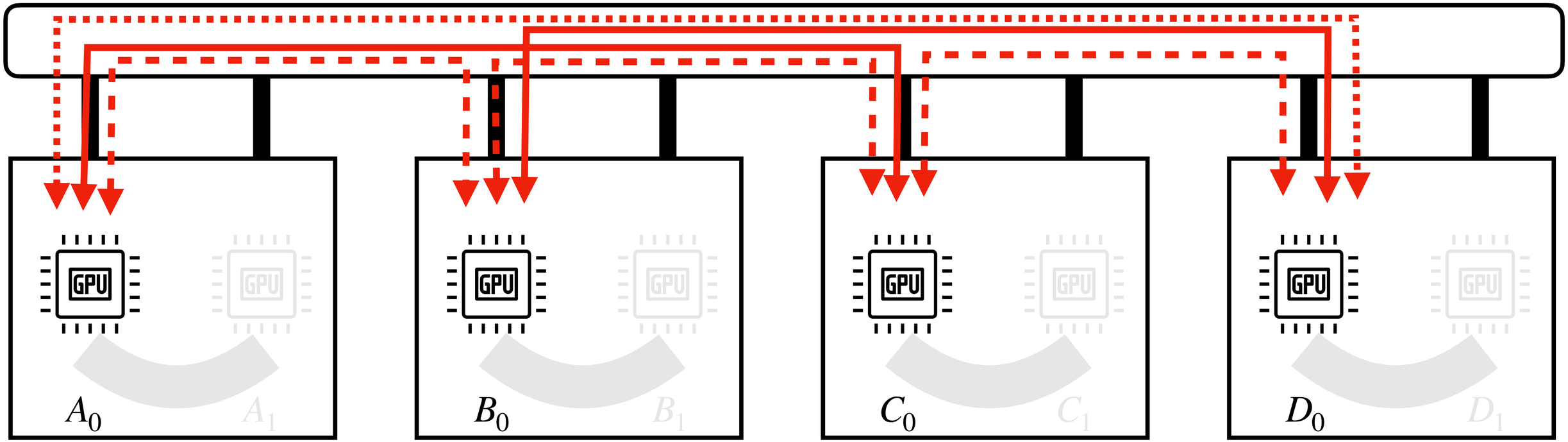


Optimal scale-out transfers with no incast



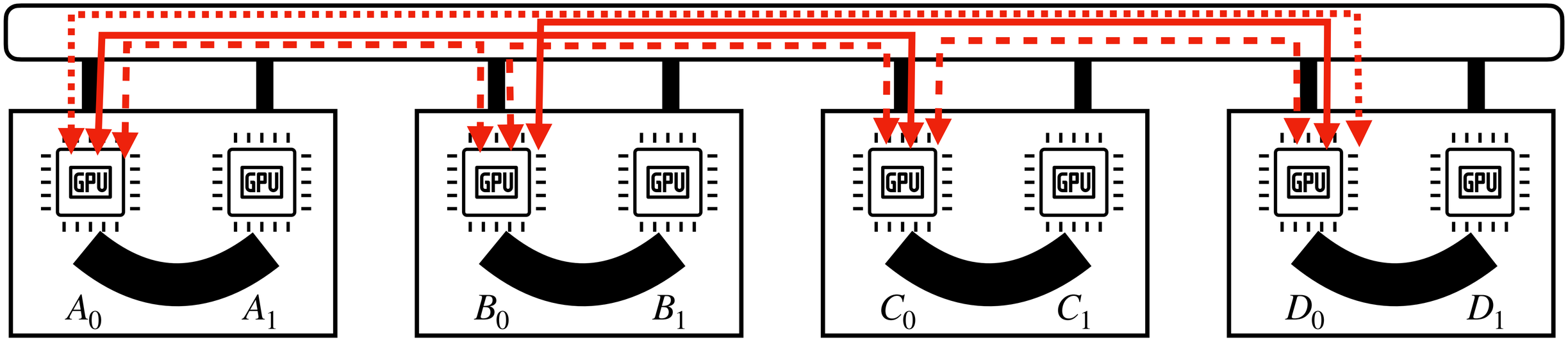
Optimal scale-out transfers with no incast

Birkhoff-Von Neumann Decomposition, 1946



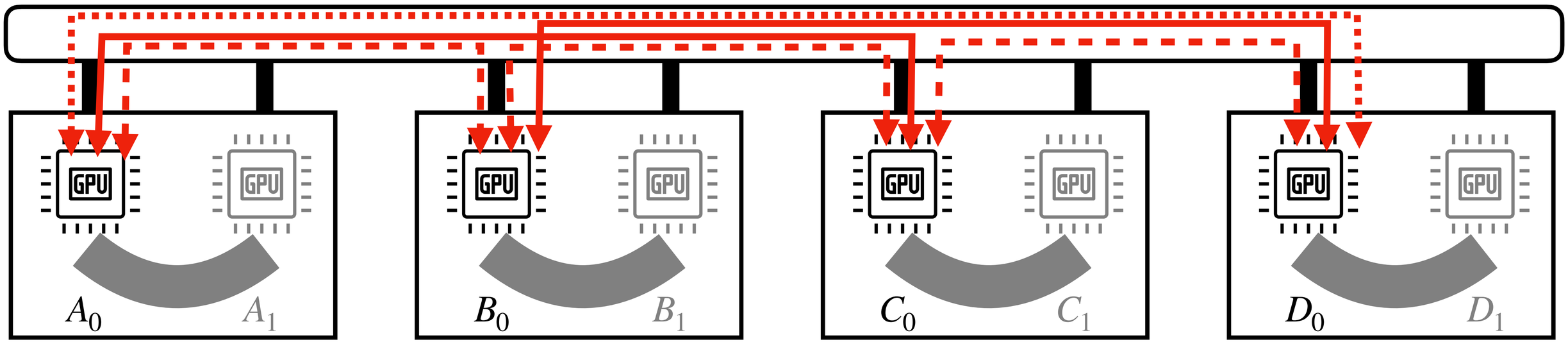
Example of incast-free transfer stages

Send \ Receive	A_0	B_0	C_0	D_0
A_0	0	0	3	2
B_0	5	0	0	4
C_0	4	2	0	3
D_0	0	7	2	0



Example of incast-free transfer stages

Send \ Receive	A_0	B_0	C_0	D_0
A_0	0	0	3	2
B_0	5	0	0	4
C_0	4	2	0	3
D_0	0	7	2	0



Example of incast-free transfer stages

Send \ Receive	A_0	B_0	C_0	D_0
A_0	0	0	3	2
B_0	5	0	0	4
C_0	4	2	0	3
D_0	0	7	2	0

=

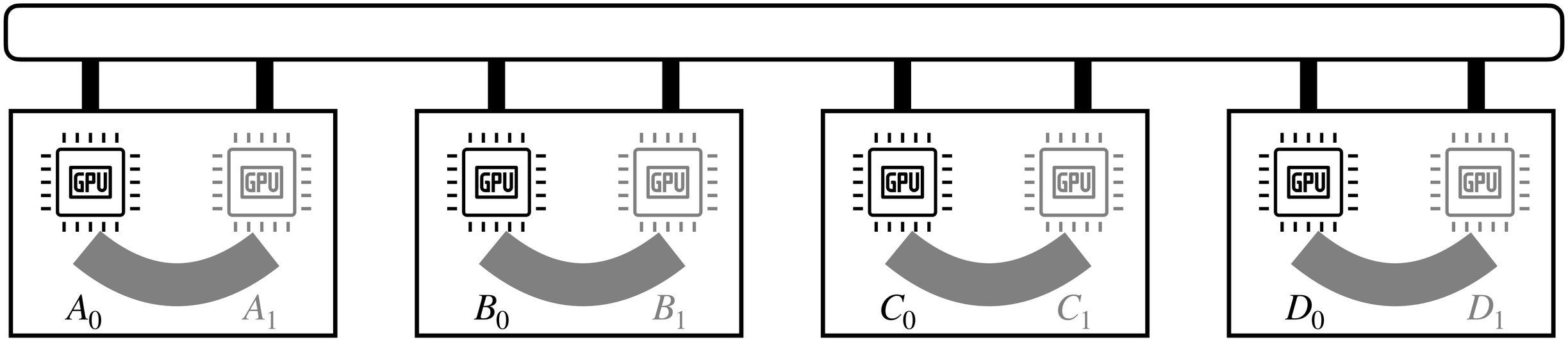
①			
0	0	3	0
3	0	0	0
0	0	0	3
0	3	0	0

+

②			
0	0	0	2
2	0	0	0
0	2	0	0
0	0	2	0

+

③			
0	0	0	0
0	0	0	4
4	0	0	0
0	4	0	0



Example of incast-free transfer stages

Send \ Receive	A_0	B_0	C_0	D_0
A_0	0	0	3	2
B_0	5	0	0	4
C_0	4	2	0	3
D_0	0	7	2	0

=

① (3, 3, 3, 3)

0	0	3	0
3	0	0	0
0	0	0	3
0	3	0	0

+

②

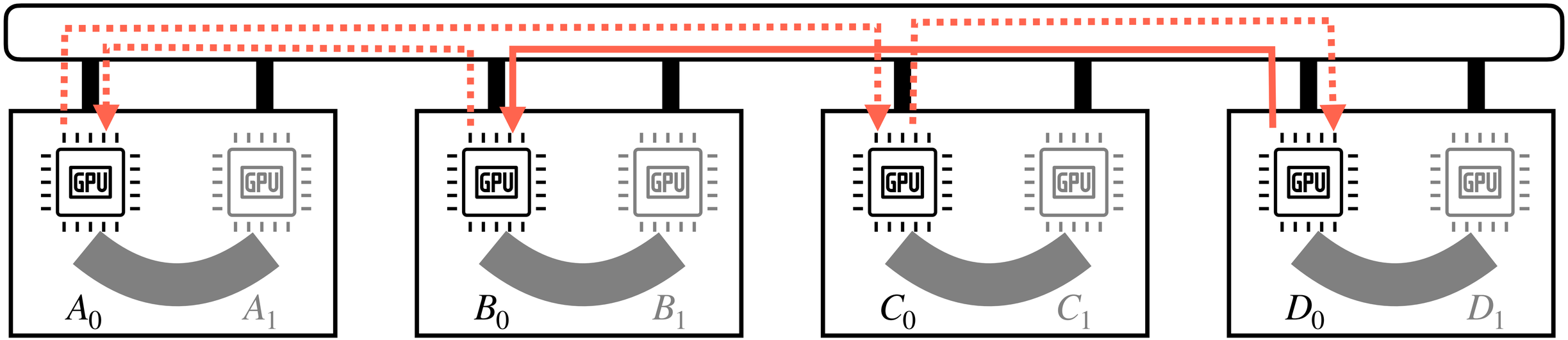
0	0	0	2
2	0	0	0
0	2	0	0
0	0	2	0

+

③

0	0	0	0
0	0	0	4
4	0	0	0
0	4	0	0

Each stage: one-to-one (incase-free), equal sized



Example of incast-free transfer stages

Send \ Receive	A_0	B_0	C_0	D_0
A_0	0	0	3	2
B_0	5	0	0	4
C_0	4	2	0	3
D_0	0	7	2	0

=

①

0	0	3	0
3	0	0	0
0	0	0	3
0	3	0	0

+

②

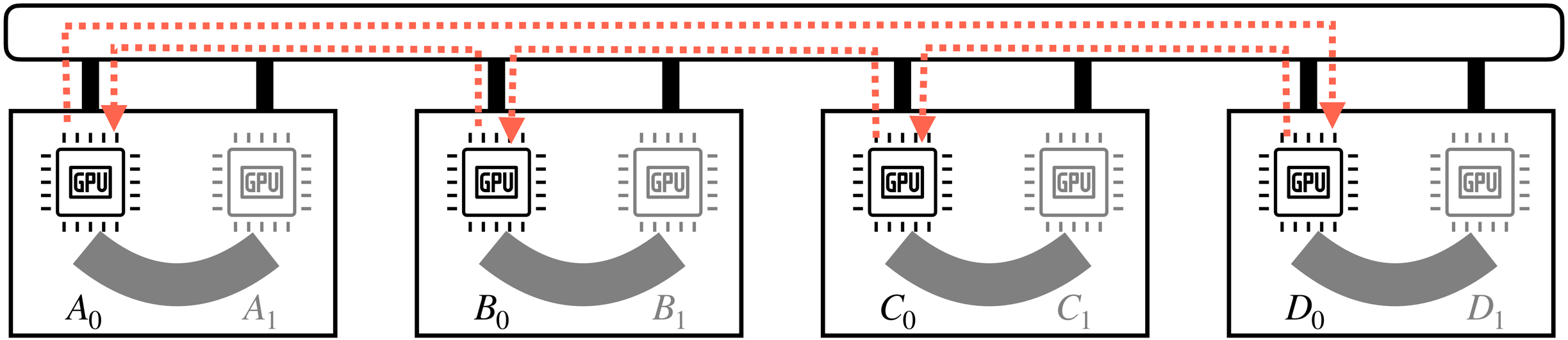
0	0	0	2
2	0	0	0
0	2	0	0
0	0	2	0

+

③

0	0	0	0
0	0	0	4
4	0	0	0
0	4	0	0

Each stage: one-to-one (incase-free), equal sized



Example of incast-free transfer stages

Send \ Receive	A_0	B_0	C_0	D_0
A_0	0	0	3	2
B_0	5	0	0	4
C_0	4	2	0	3
D_0	0	7	2	0

=

①

0	0	3	0
3	0	0	0
0	0	0	3
0	3	0	0

+

②

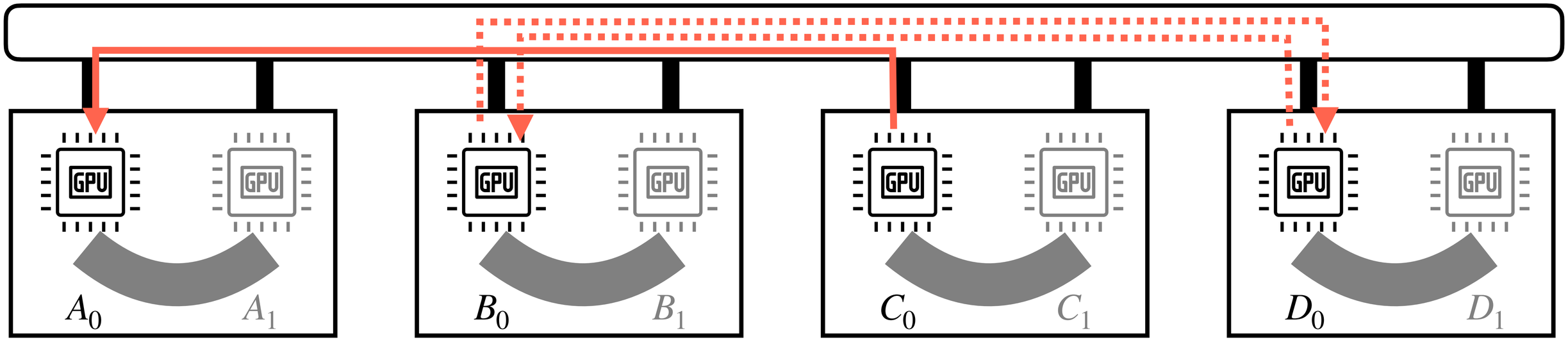
0	0	0	2
2	0	0	0
0	2	0	0
0	0	2	0

+

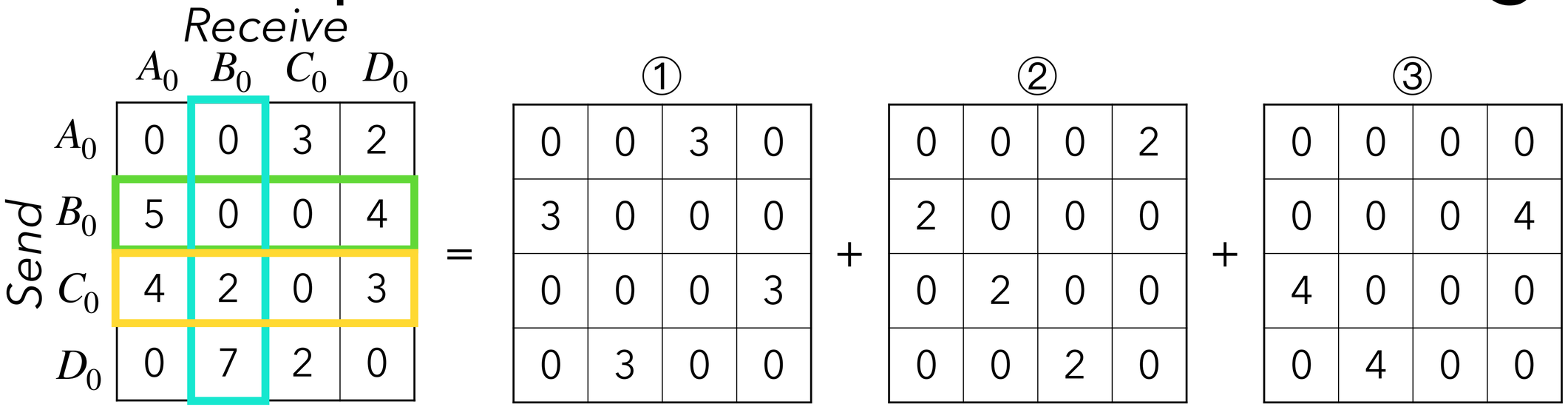
③

0	0	0	0
0	0	0	4
4	0	0	0
0	4	0	0

Each stage: one-to-one (incase-free), equal sized



Example of incast-free transfer stages



9s lower bound
(max row/col sum)

match ←

Stage times = 3s + 2s + 4s = 9s

The scale-out bound is still set by the largest senders/receivers

	A_0	B_0	C_0	D_0
A_0	0	0	3	2
B_0	5	0	0	4
C_0	4	2	0	3
D_0	0	7	2	0

bound = **max row/col sum**

The scale-out bound is still set by the largest senders/receivers

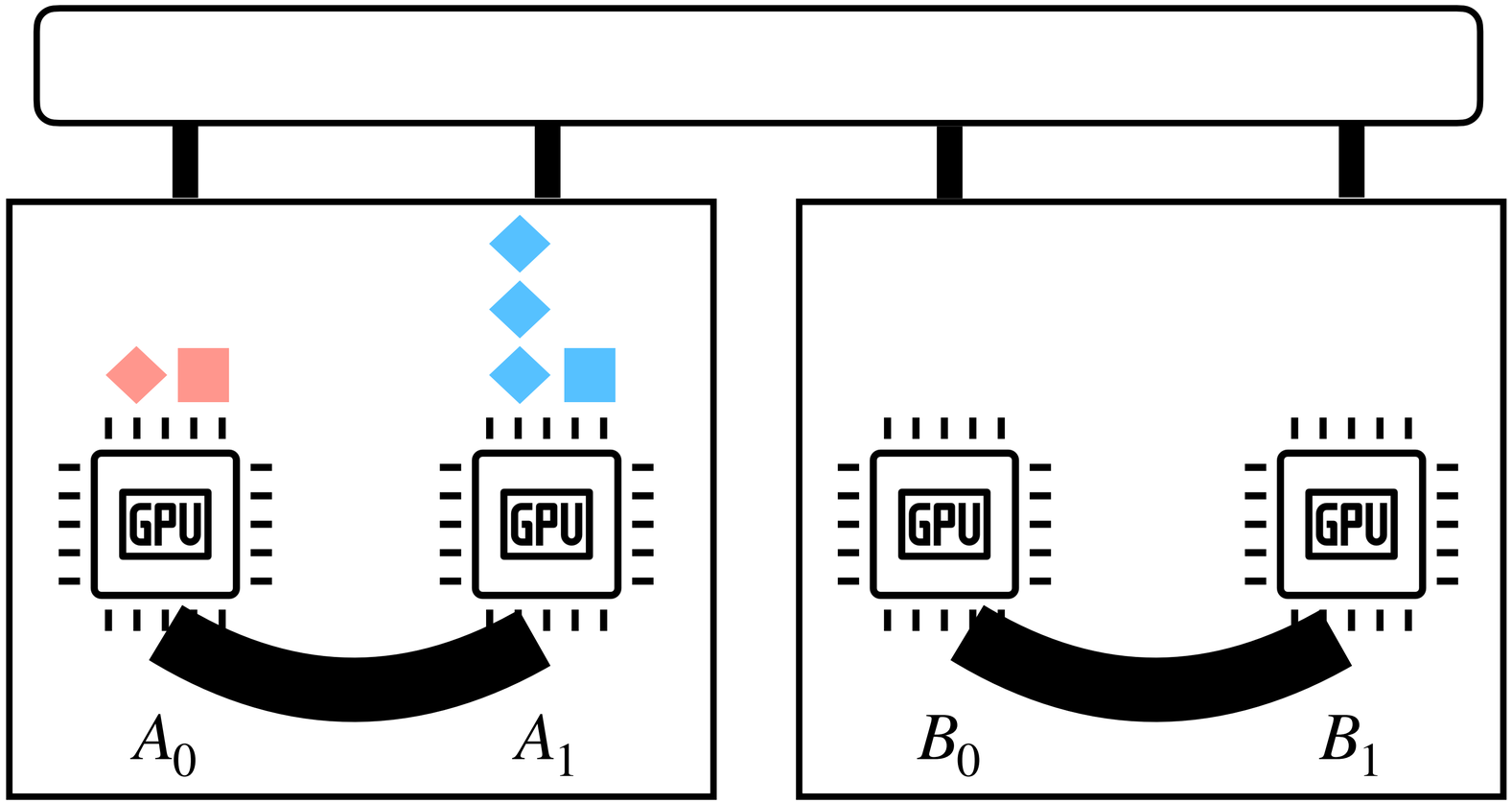
Global Scheduling on Scale-out

(Reduce largest row/column sum)

Local Scheduling on Scale-up

With free scale-up, waypointing becomes simple

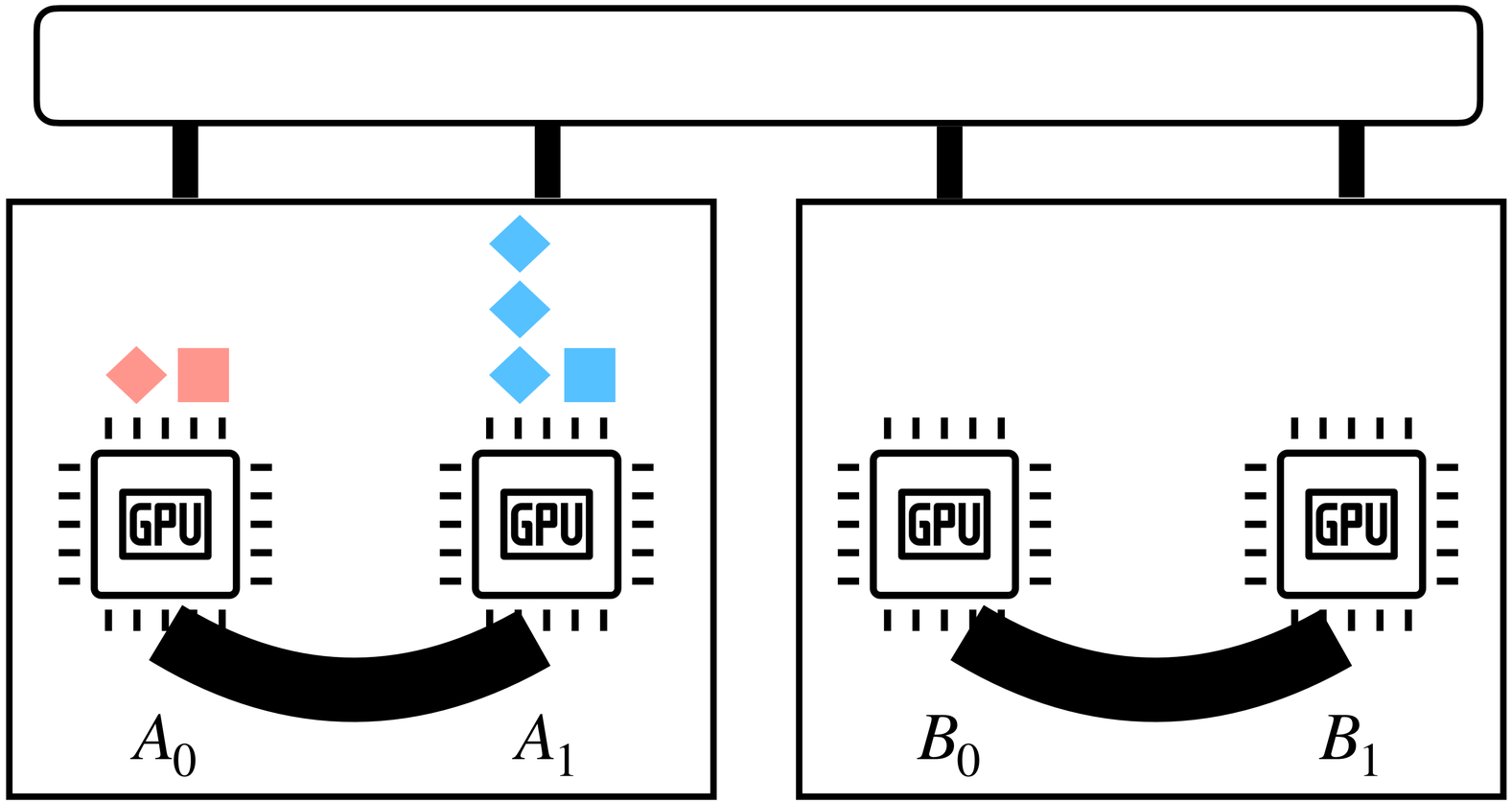
Target#1: reduce the heaviest scale-out **sending** load



Send \ *Receive*	B_0	B_1
A_0	1	1
A_1	3	1

With free scale-up, waypointing becomes simple

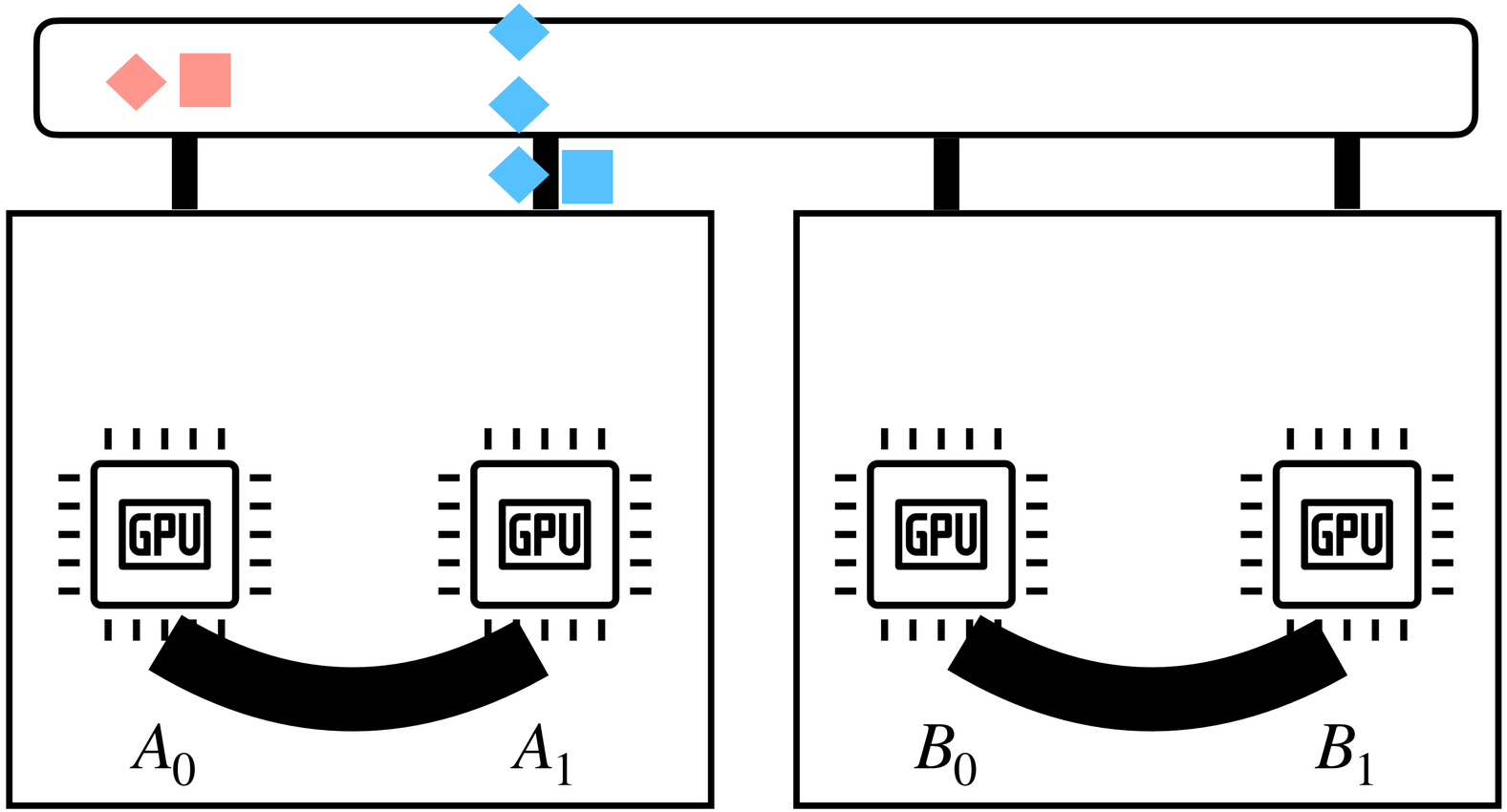
Target#1: reduce the heaviest scale-out **sending** load



Send \ *Receive*	B_0	B_1
A_0	1	1
A_1	3	1

With free scale-up, waypointing becomes simple

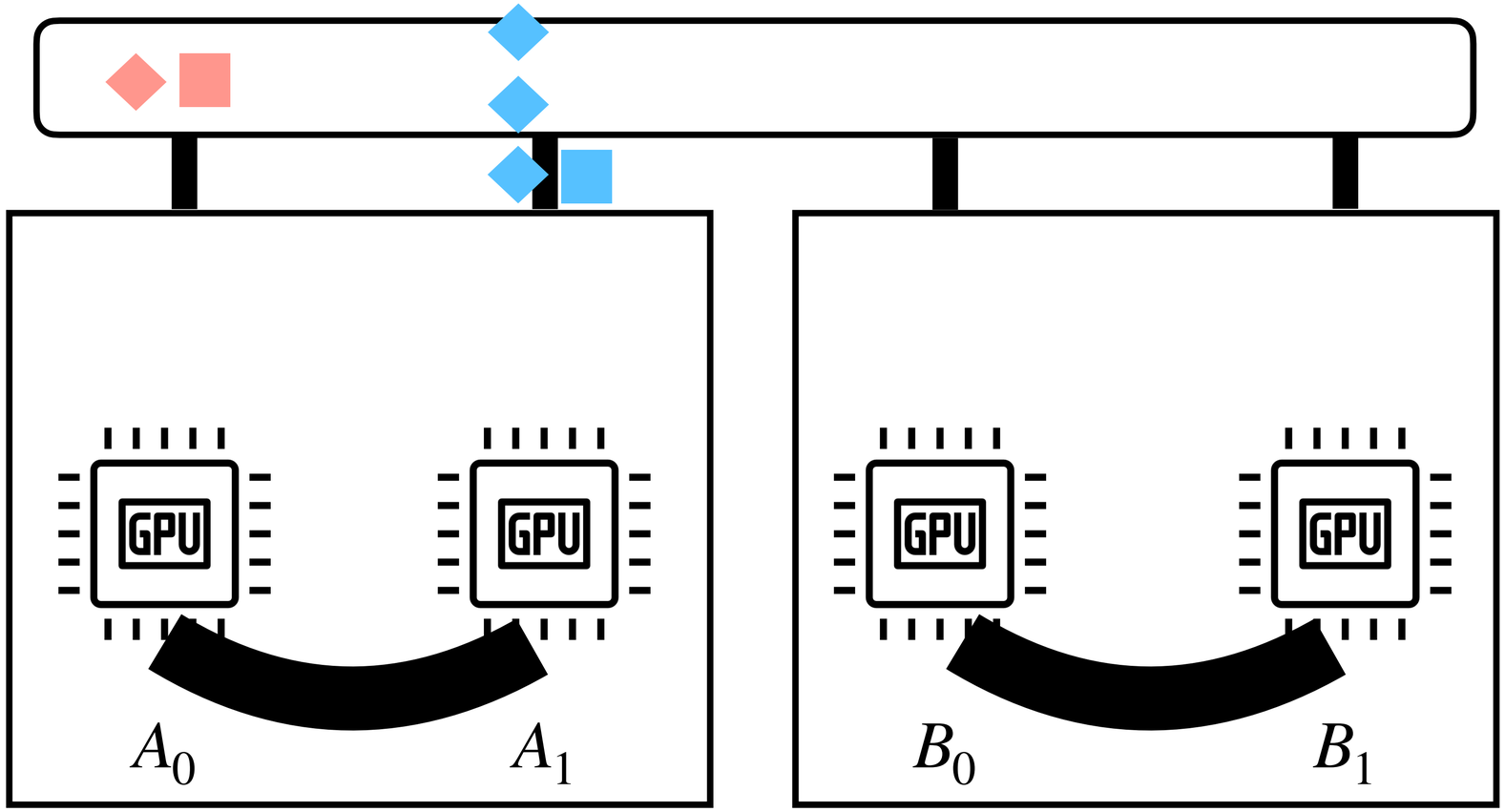
Target#1: reduce the heaviest scale-out **sending** load



Send \ *Receive*	B_0	B_1
A_0	1	1
A_1	3	1

With free scale-up, waypointing becomes simple

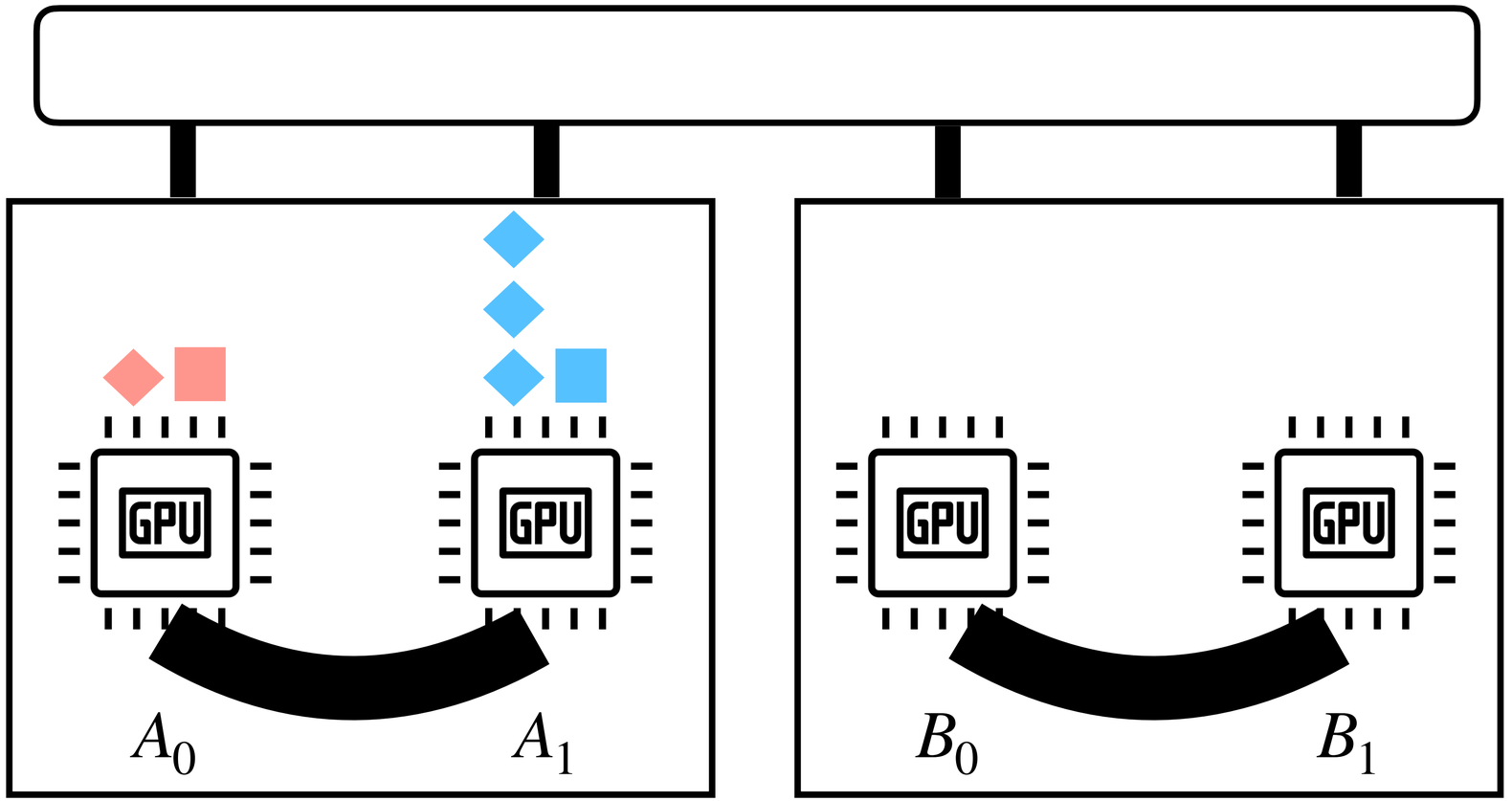
Target#1: reduce the heaviest scale-out **sending** load



Send \ Receive	B_0	B_1	
A_0	1	1	$\sum = 2$
A_1	3	1	$\sum = 4$

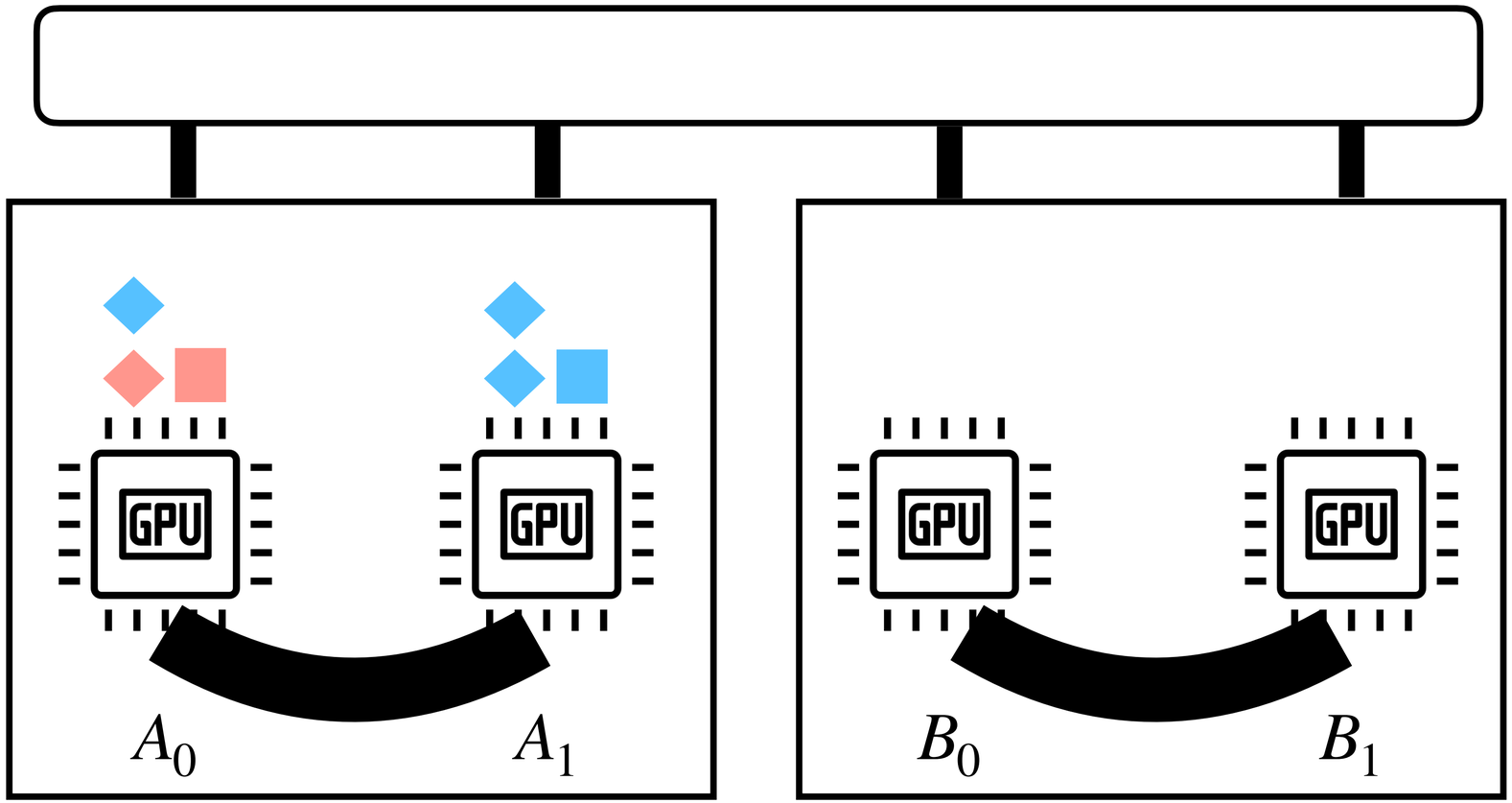
Sender straggler A_1

Solution#1: rebalance sender load locally



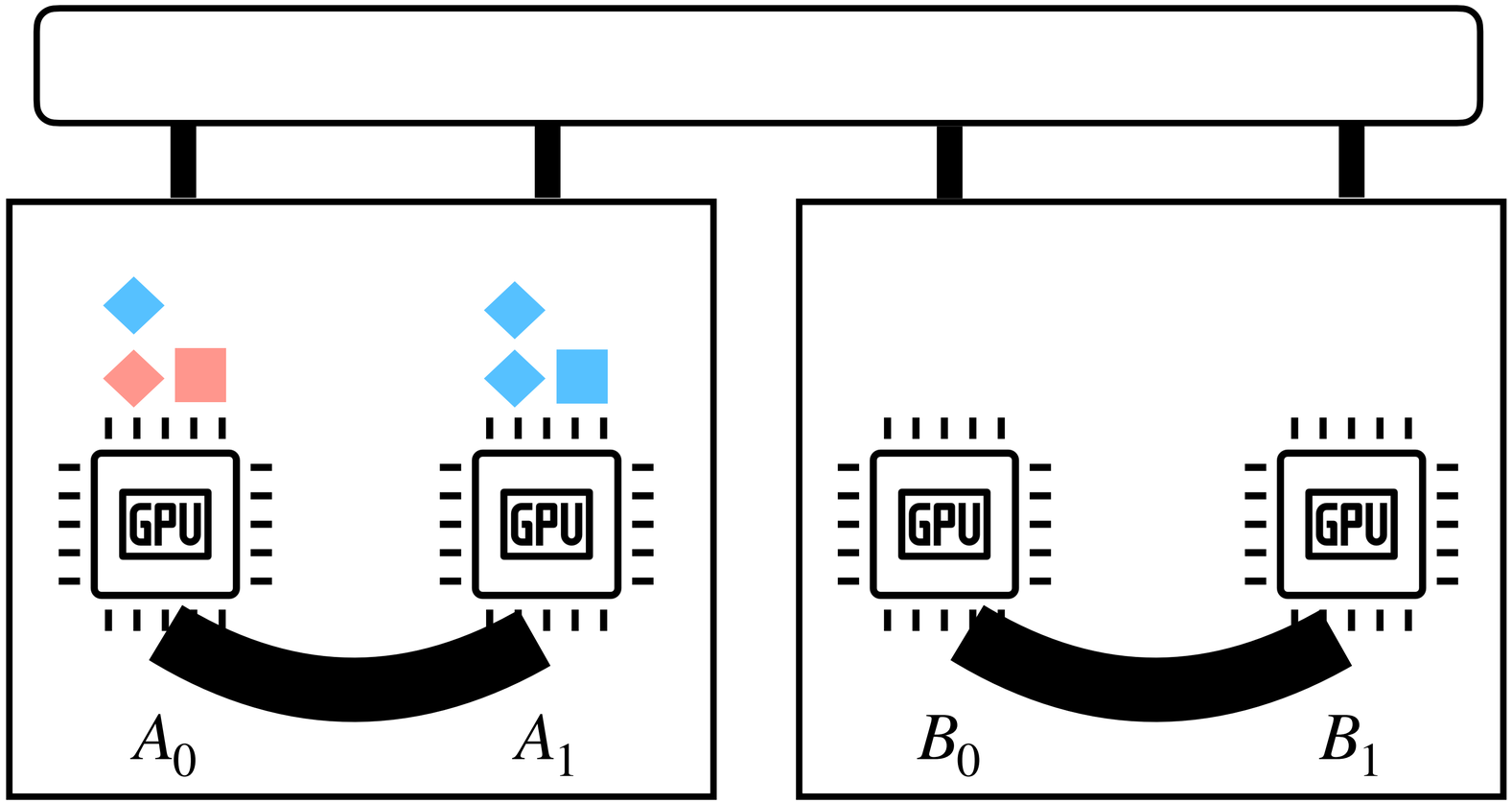
	B_0	B_1
A_0	1	1
A_1	3	1

Solution#1: rebalance sender load locally



	B_0	B_1
A_0	1	1
A_1	3	1

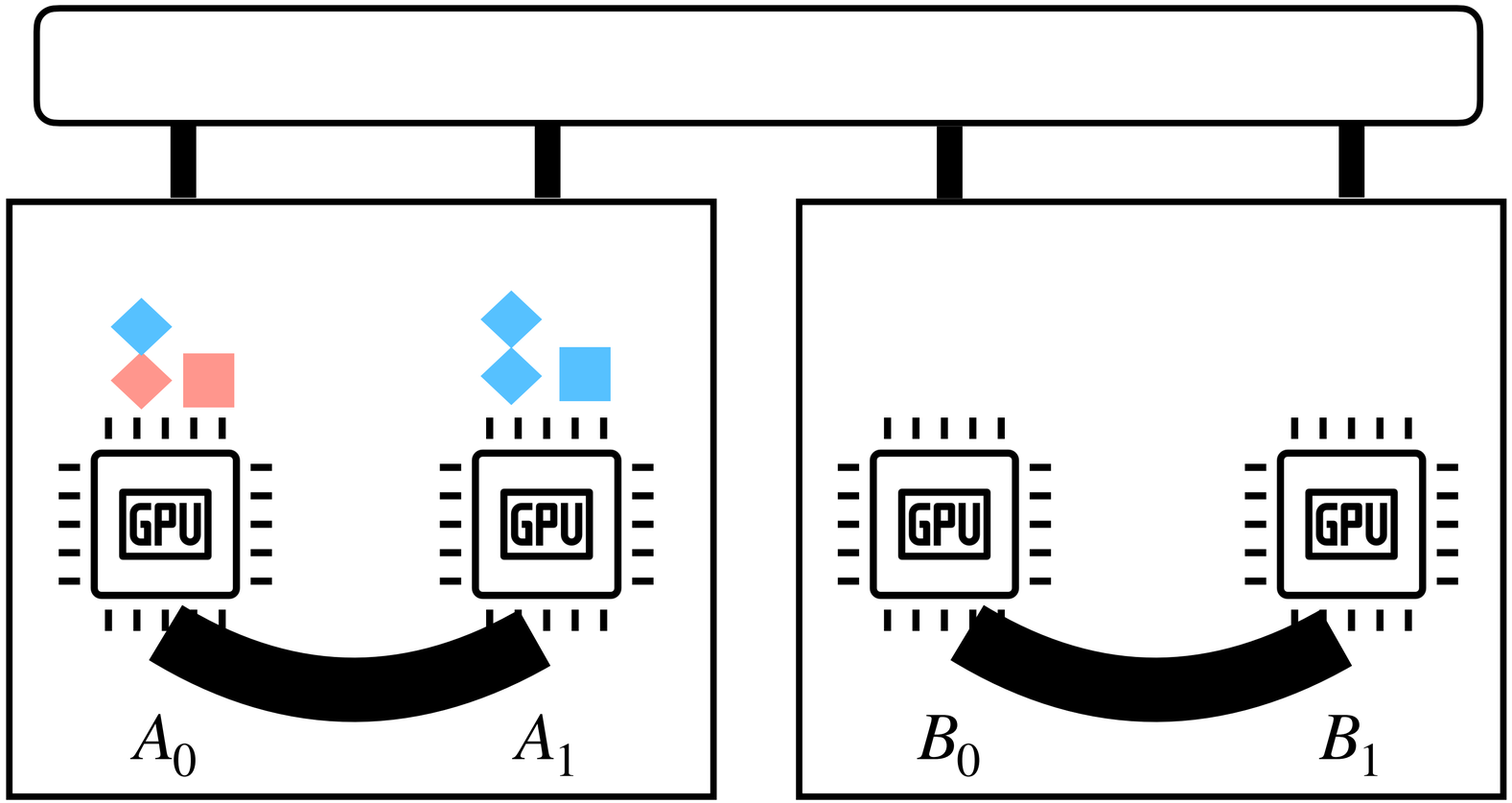
Solution#1: rebalance sender load locally



	B_0	B_1	
A_0	2	1	$\sum = 3$
A_1	2	1	$\sum = 3$

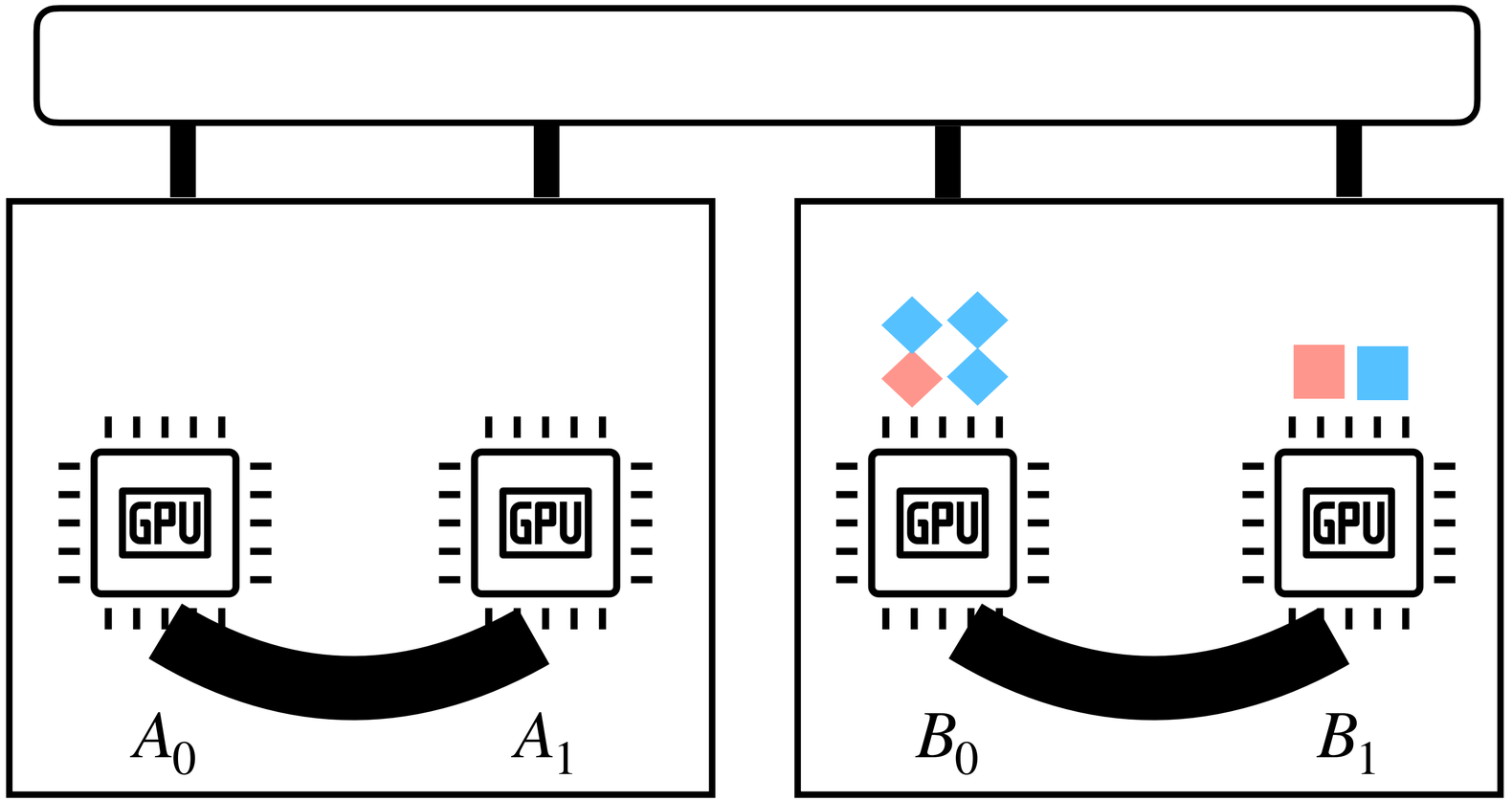
No sender stragglers!

Target#2: reduce the heaviest scale-out **receiving** load



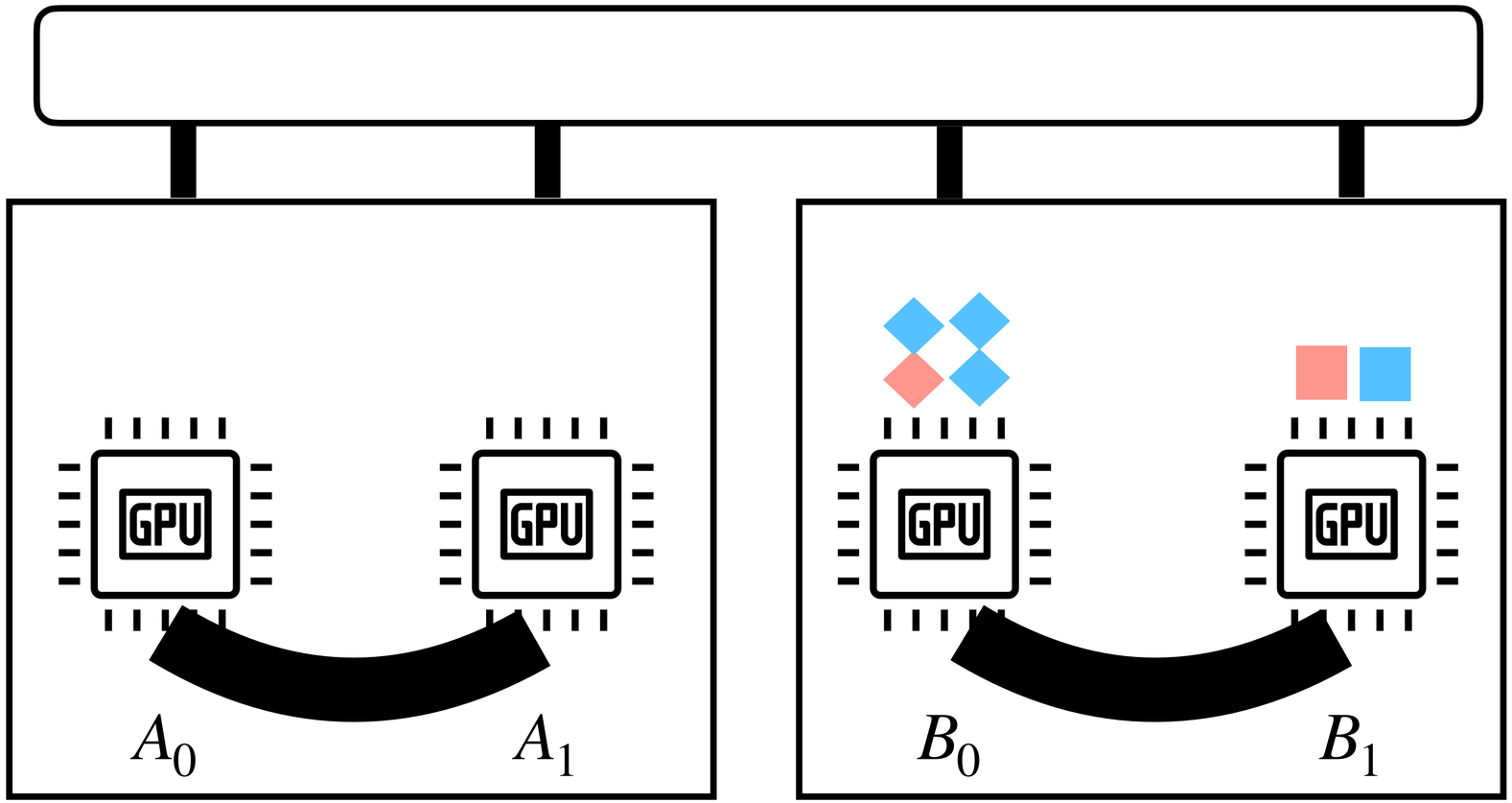
	B_0	B_1
A_0	2	1
A_1	2	1

Target#2: reduce the heaviest scale-out **receiving** load



	B_0	B_1
A_0	2	1
A_1	2	1

Target#2: reduce the heaviest scale-out **receiving** load

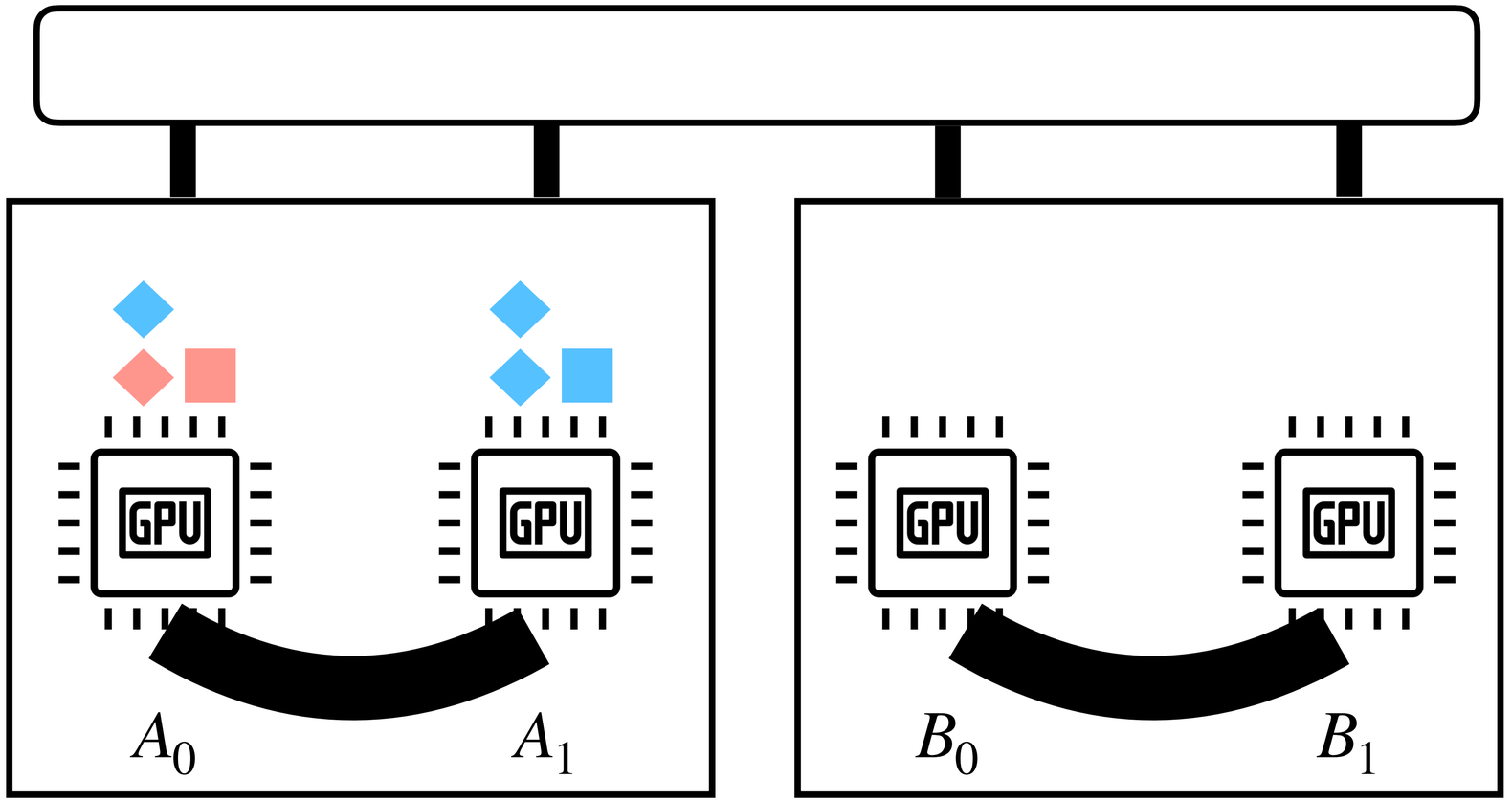


	B_0	B_1
A_0	2	1
A_1	2	1

$\sum = 4$ $\sum = 2$

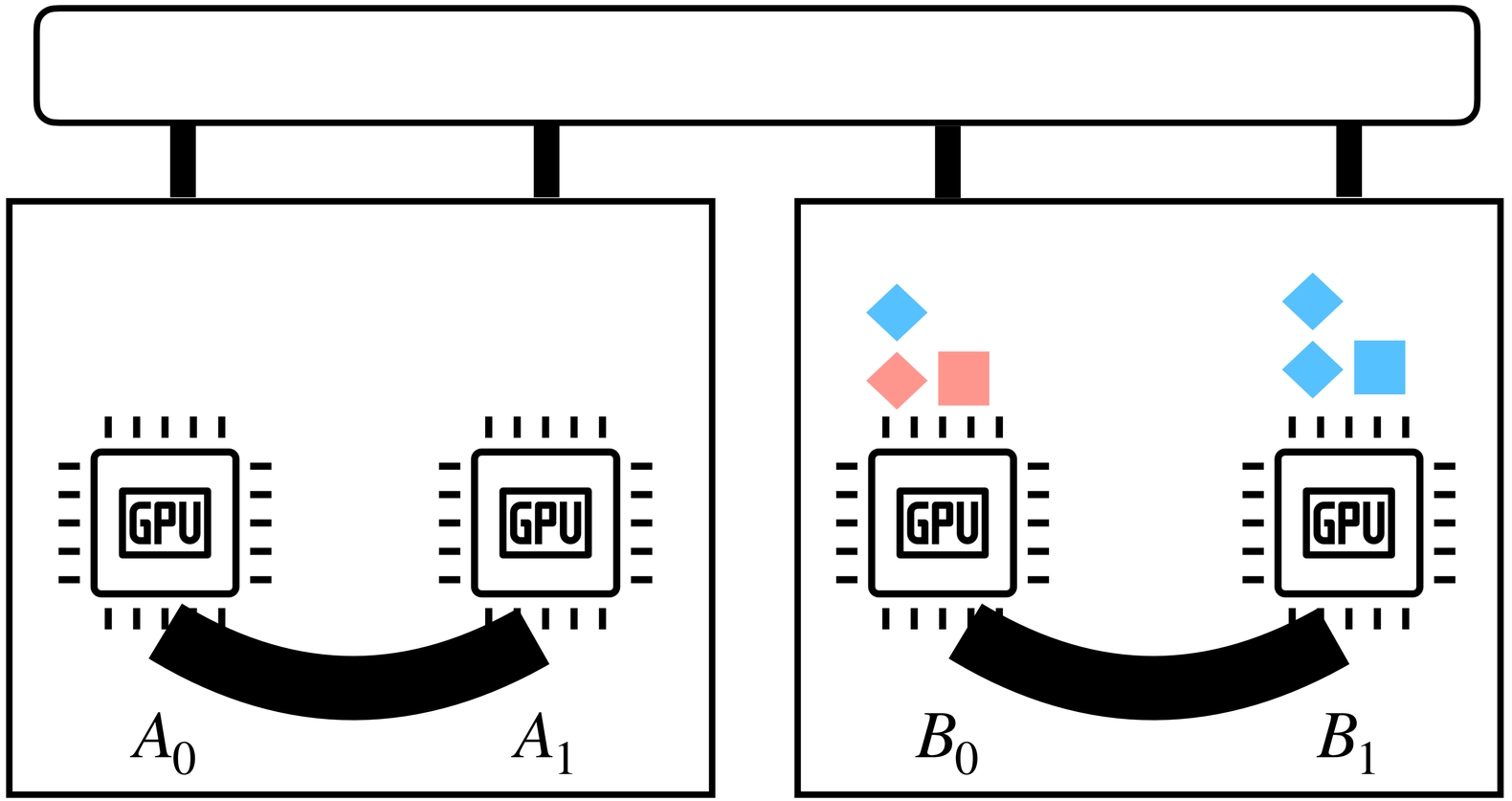
Receiver straggler B_0

Solution#2: pack by destination server



	B_0	B_1
A_0	2	1
A_1	2	1

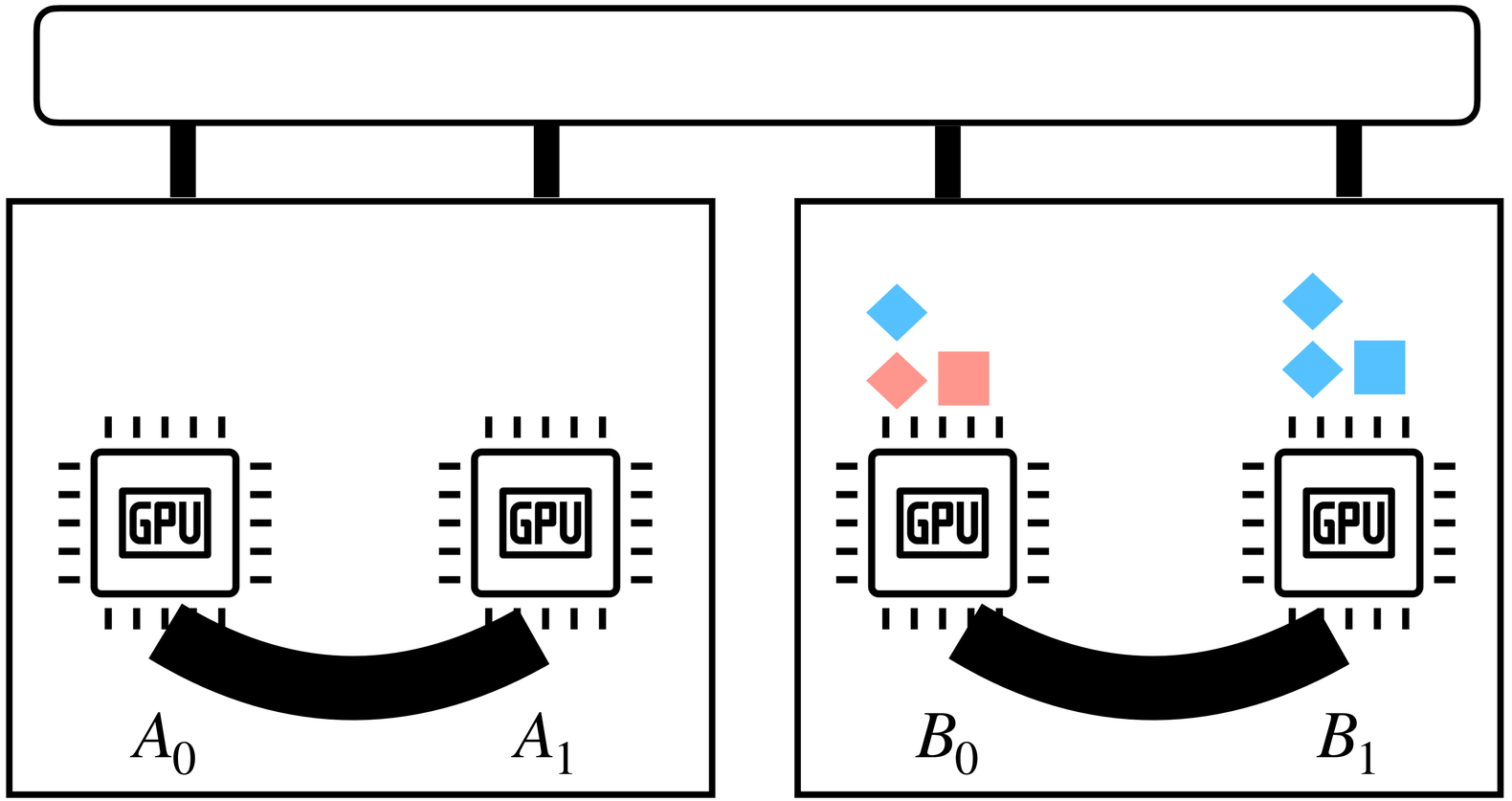
Solution#2: pack by destination server



	B_0	B_1
A_0	2	1
A_1	2	1

Balanced scale-out!

Solution#2: pack by destination server

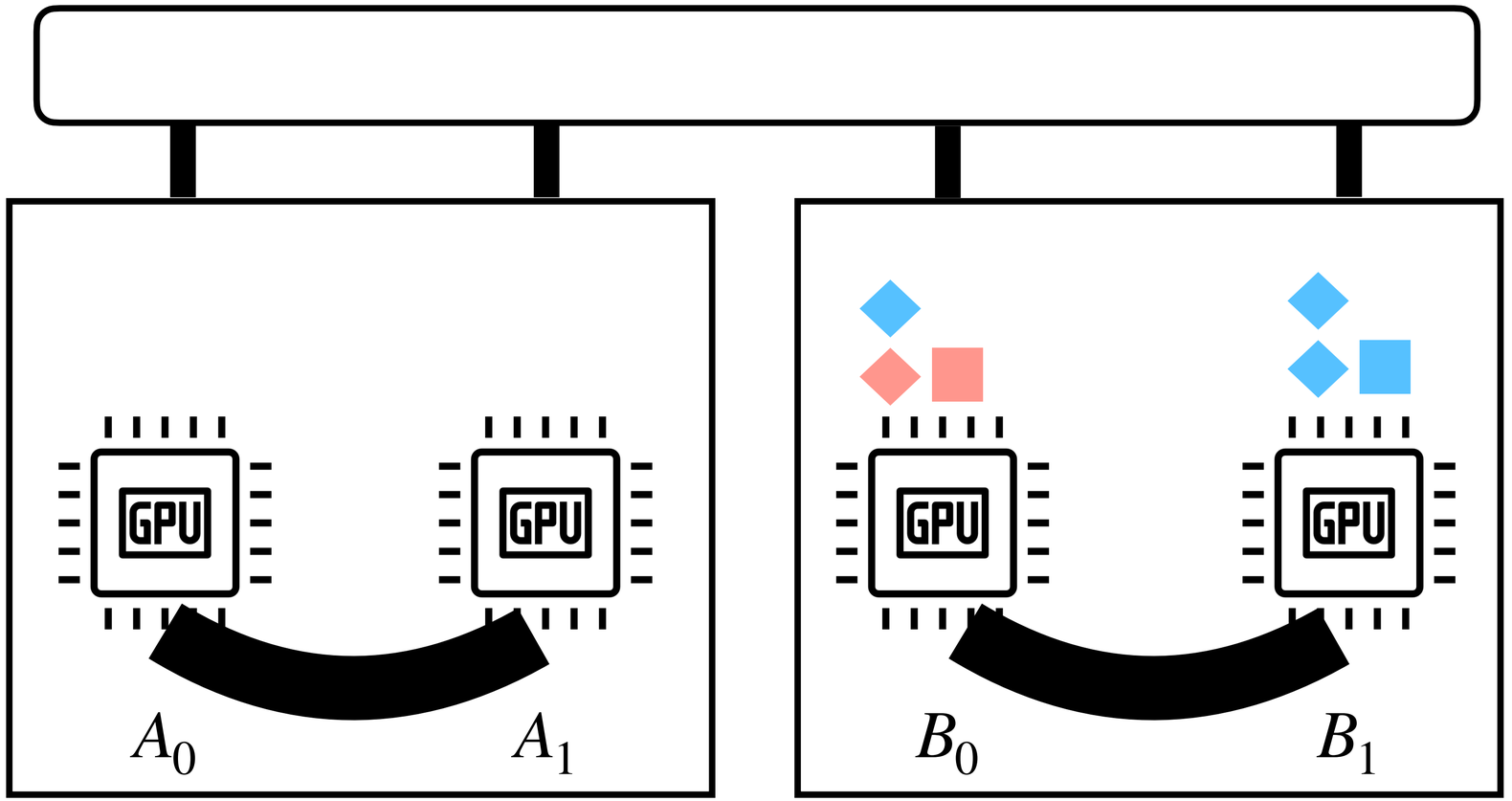


	B_0	B_1
A_0	3	0
A_1	0	3

No stragglers!

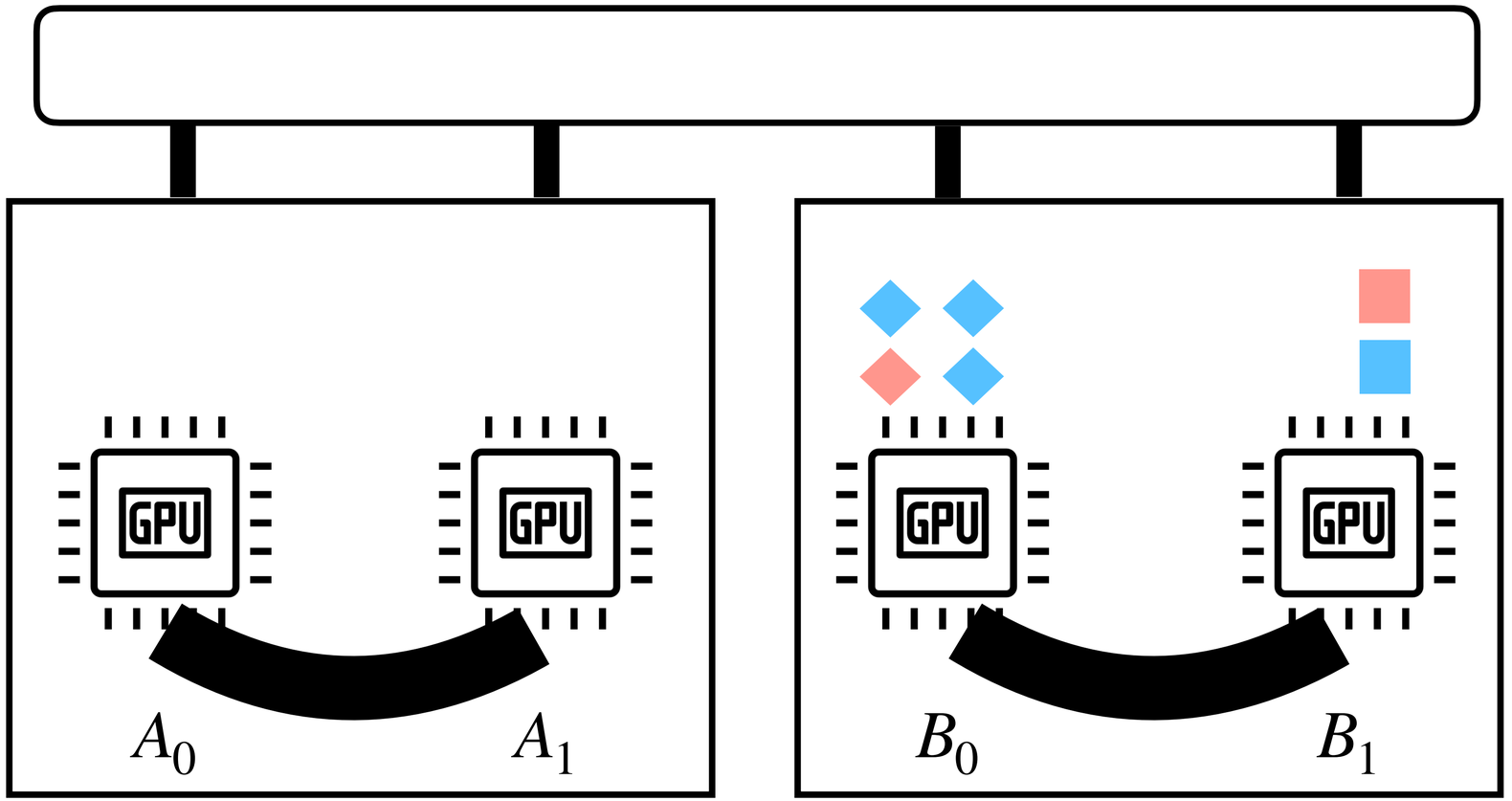
Balanced scale-out!

Fix final placement locally



	B_0	B_1
A_0	3	0
A_1	0	3

Fix final placement locally



	B_0	B_1
A_0	3	0
A_1	0	3

Faster scale-out by balancing every server pair

	A_0	A_1	B_0	B_1	C_0	C_1
A_0			6	1	1	0
A_1			1	4	1	2
B_0	0	1			2	1
B_1	0	3			5	2
C_0	4	2	2	0		
C_1	3	3	1	1		

Faster scale-out by balancing every server pair

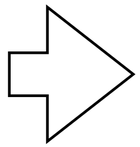
	A_0	A_1	B_0	B_1	C_0	C_1
A_0			6	1	1	0
A_1			1	4	1	2
B_0	0	1			2	1
B_1	0	3			5	2
C_0	4	2	2	0		
C_1	3	3	1	1		

$$\sum = 10$$

Faster scale-out by balancing every server pair

	A_0	A_1	B_0	B_1	C_0	C_1
A_0			6	1	1	0
A_1			1	4	1	2
B_0	0	1			2	1
B_1	0	3			5	2
C_0	4	2	2	0		
C_1	3	3	1	1		

$$\sum = 10$$

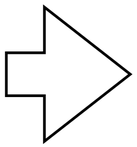


		6	0	2	0
		0	6	0	2
2	0			5	0
0	2			0	5
6	0	2	0		
0	6	0	2		

Faster scale-out by balancing every server pair

	A_0	A_1	B_0	B_1	C_0	C_1
A_0			6	1	1	0
A_1			1	4	1	2
B_0	0	1			2	1
B_1	0	3			5	2
C_0	4	2	2	0		
C_1	3	3	1	1		

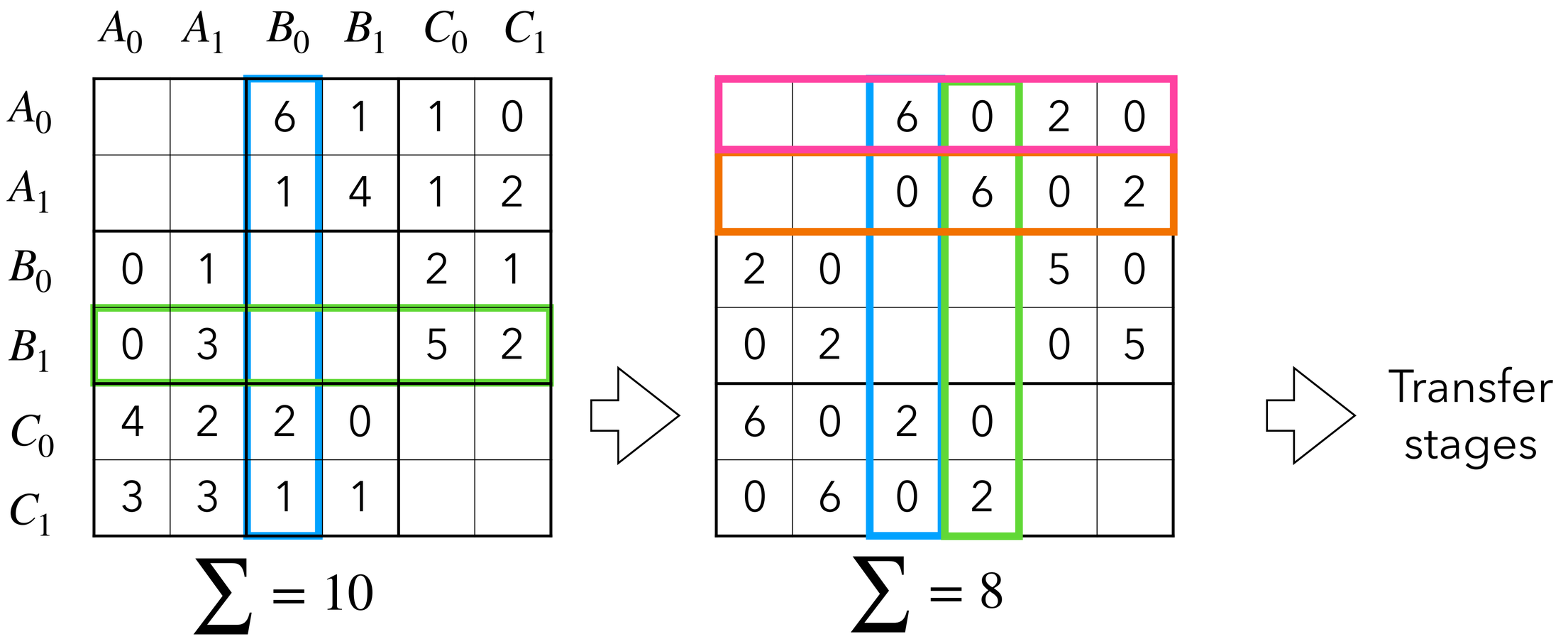
$\sum = 10$



		6	0	2	0
		0	6	0	2
2	0			5	0
0	2			0	5
6	0	2	0		
0	6	0	2		

$\sum = 8$

Faster scale-out by balancing every server pair



But scale-up is not free, so FAST pipelines it

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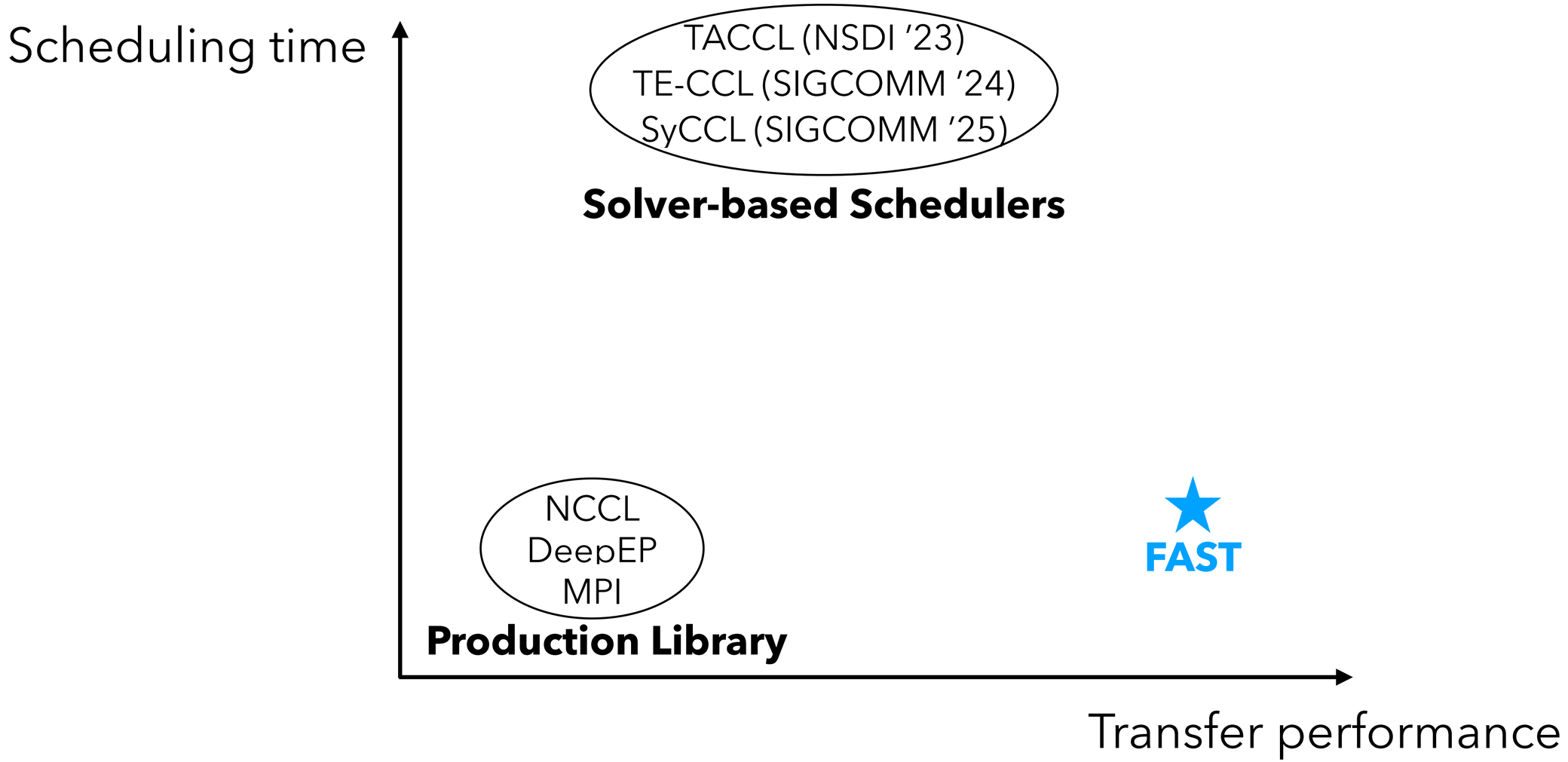
- Scale-up is merely 9x faster

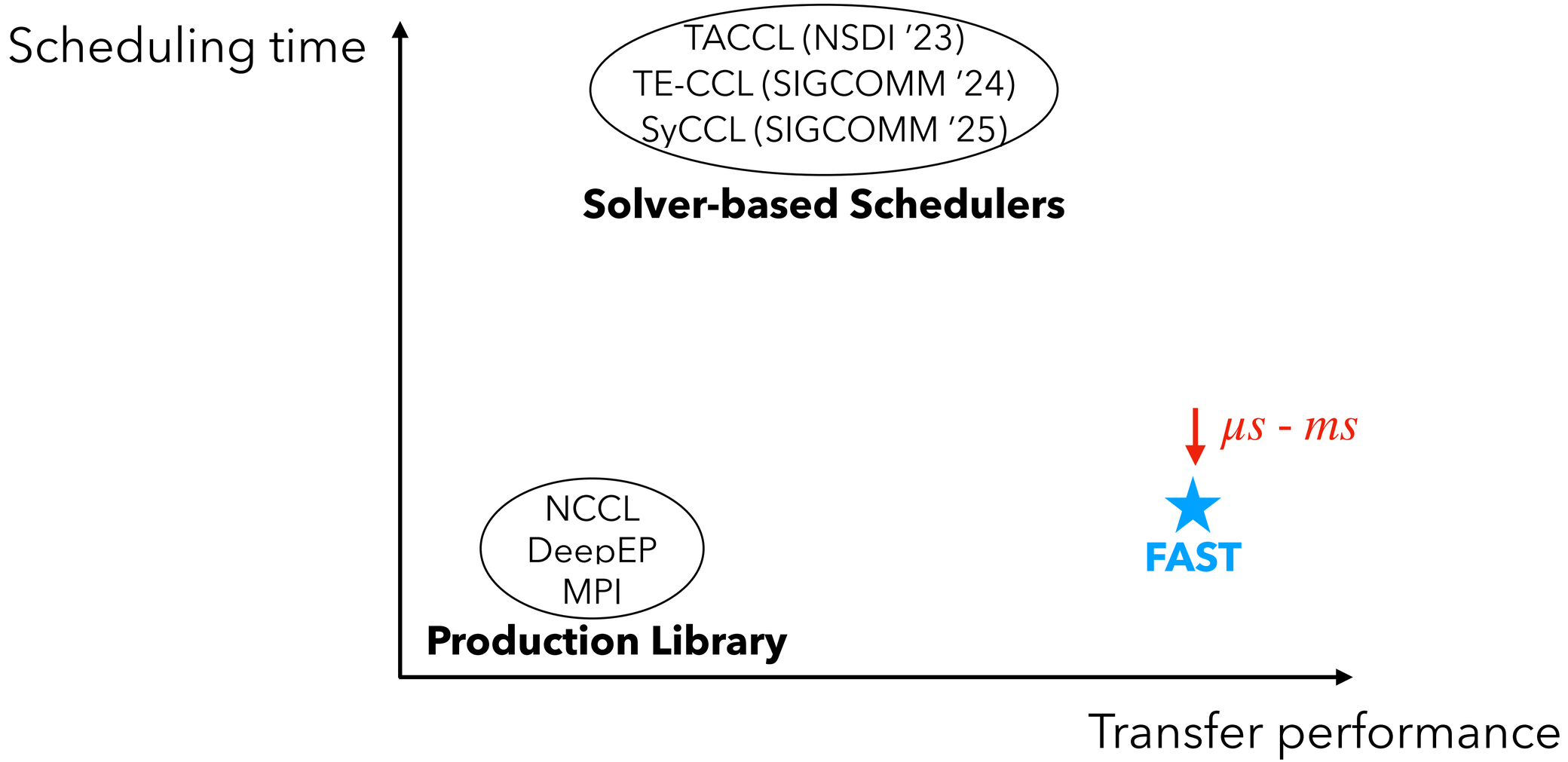
But scale-up is not free, so FAST pipelines it

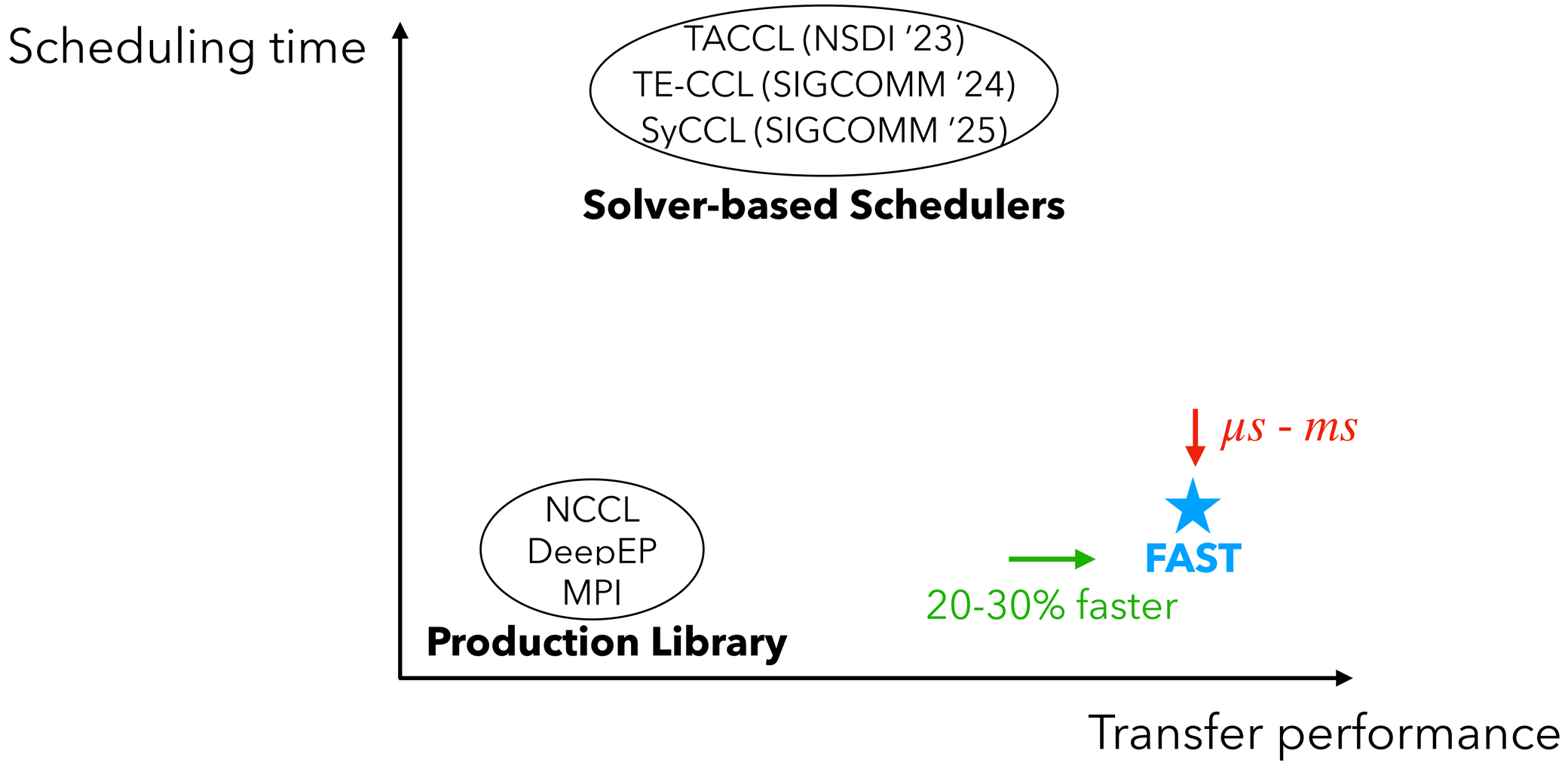
- Scale-up is merely 9x faster
- Pipeline scale-up with scale-out to hide most extra scale-up transfers

But scale-up is not free, so FAST pipelines it

- Scale-up is merely 9x faster
- Pipeline scale-up with scale-out to hide most extra scale-up transfers
- Within 2.1x of an oracle bound in worst case
    - Empirically, 1.2x of that bound


Scheduling time
TACCL (NSDI '23)
TE-CCL (SIGCOMM '24)
SyCCL (SIGCOMM '25)
Solver-based Schedulers
NCCL
DeepEP
MPI
Production Library
FAST
Transfer performance

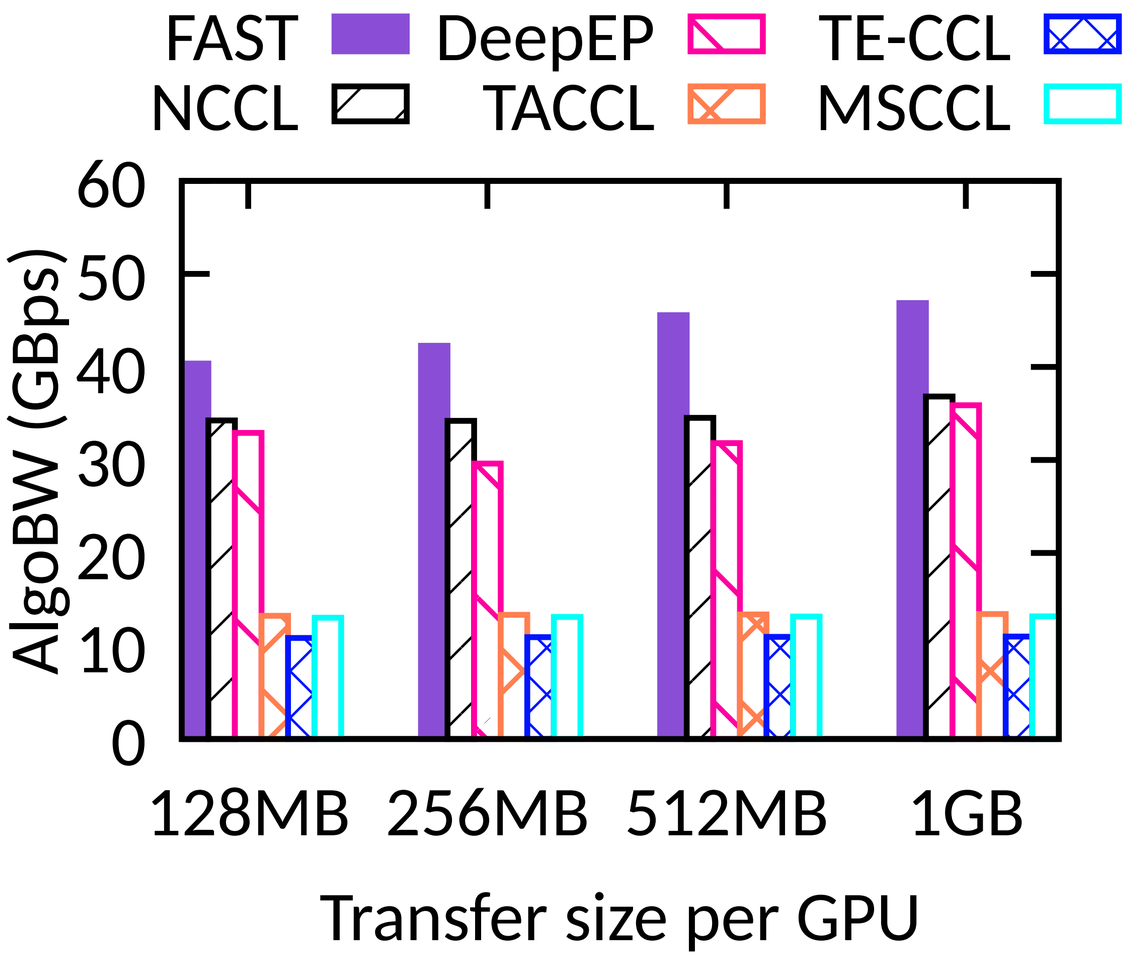

Scheduling time
TACCL (NSDI '23)
TE-CCL (SIGCOMM '24)
SyCCL (SIGCOMM '25)
Solver-based Schedulers
μs - ms
FAST
NCCL
DeepEP
MPI
Production Library
Transfer performance


Scheduling time
TACCL (NSDI '23)
TE-CCL (SIGCOMM '24)
SyCCL (SIGCOMM '25)
Solver-based Schedulers
μs - ms
FAST
20-30% faster
NCCL
DeepEP
MPI
Production Library
Transfer performance

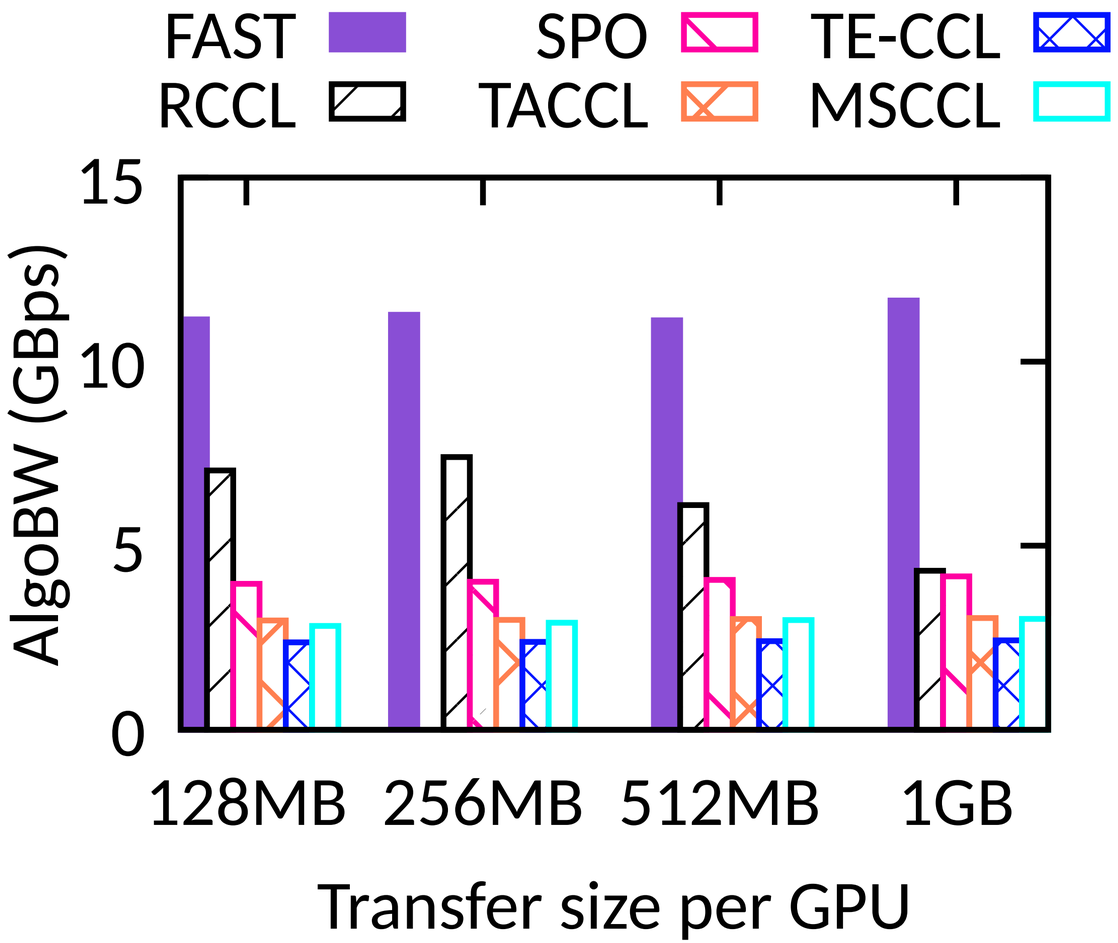
Implementation & evaluation setup

	NVIDIA	**AMD**
Software stack	NVSHMEM	RCCL
GPU model	H200	MI300X
Scale-up vs scale-out	450 vs 50 GBps (x9 gap)	448 vs 12.5 GBps (x36 gap)
Workload	Skewed traffic with Zipf distribution	
Scale	32 GPUs, 8 GPU-per-server	

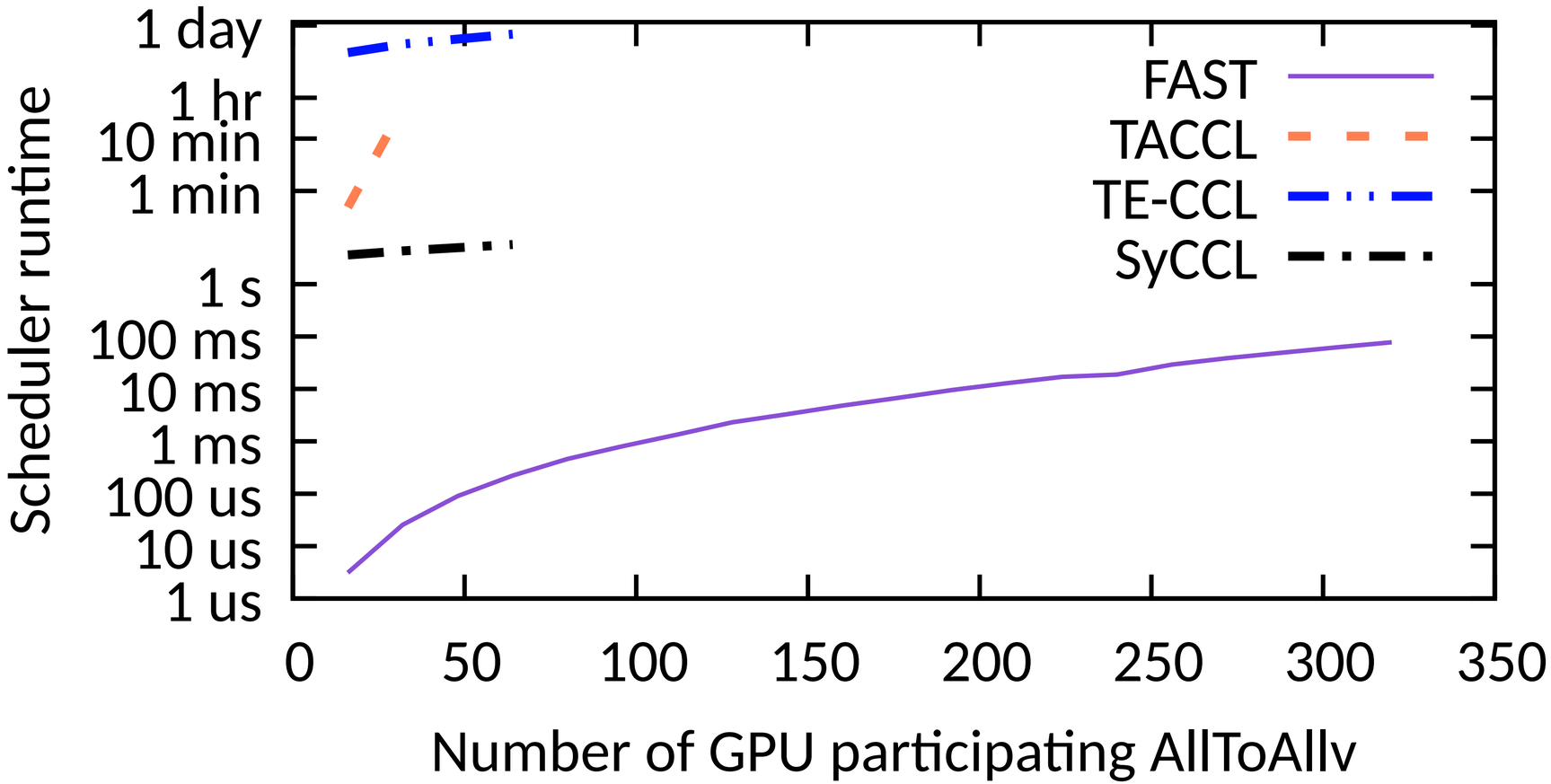
FAST achieves **1.2–1.3×** higher algorithmic bandwidth than the best **NVIDIA** baseline



FAST achieves **1.3-2.6x** higher bandwidth than the best **AMD** baseline



FAST completes in $\mu s - ms$, orders of magnitude faster than solvers



Takeaway

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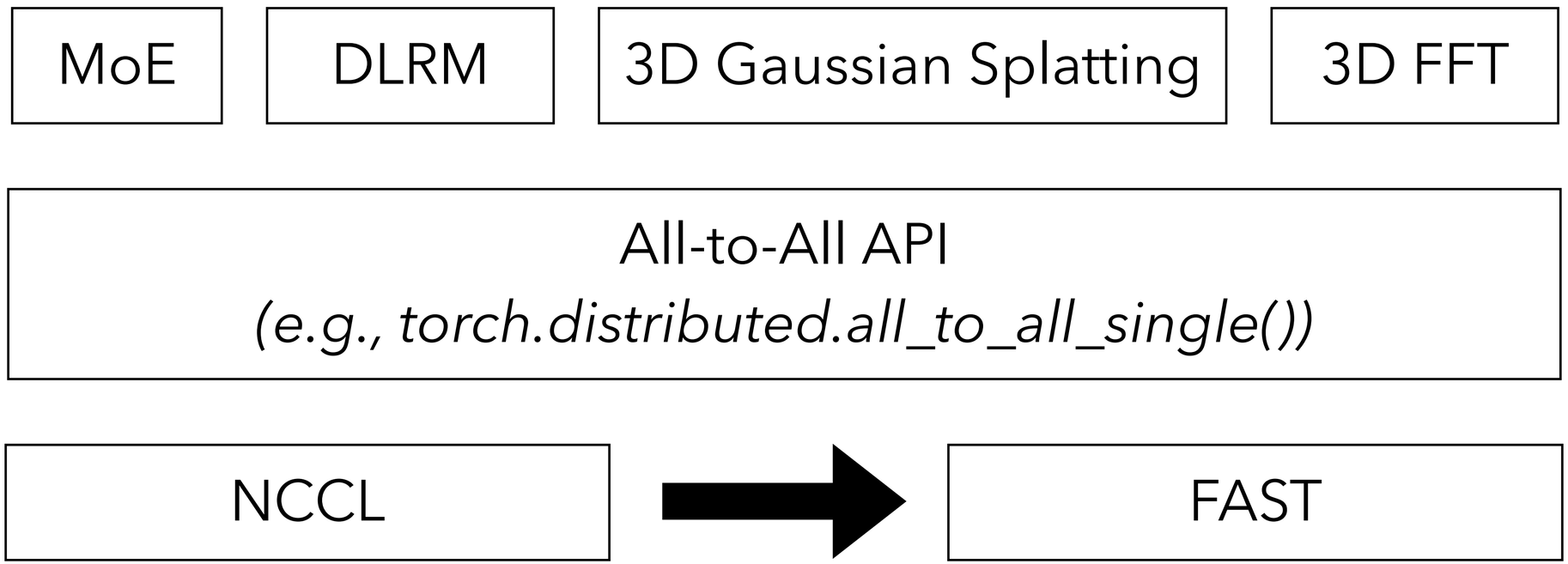
- All-to-All is hard: skew, incast, and fast-changing traffic
- FAST: reshape traffic locally to simplify global transfers
- 20-30% higher bandwidth, $\mu s - ms$ schedules

Contact: yiranlei@cs.cmu.edu

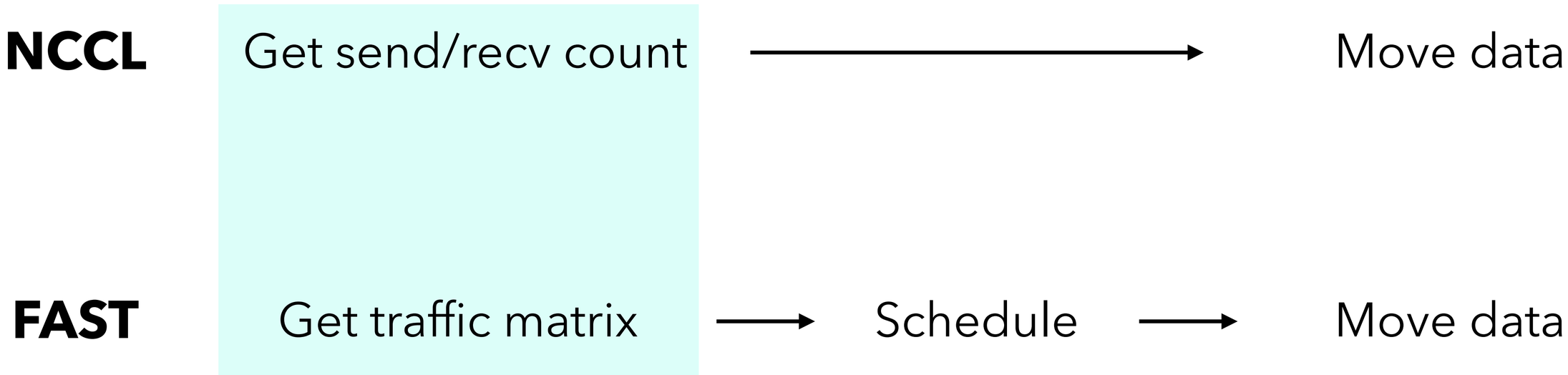
FAST is open sourced

Backup slides

FAST drops in for NCCL All-to-All



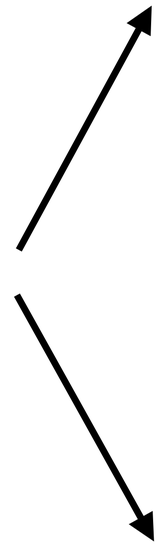
NCCL vs. FAST: where the scheduler fits



All-Gather in Megatron-LM

Birkhoff's Decomposition vs Spreadout

	A_0	B_0	C_0	D_0
A_0	0	0	3	2
B_0	5	0	0	4
C_0	4	2	0	3
D_0	0	7	2	0



Birkhoff's decomposition

0	0	3	0
3	0	0	0
0	0	0	3
0	3	0	0

3s

+

0	0	0	2
2	0	0	0
0	2	0	0
0	0	2	0

2s

+

0	0	0	0
0	0	0	4
4	0	0	0
0	4	0	0

4s

Spreadout

0	0	3	0
0	0	0	4
4	0	0	0
0	7	0	0

7s

+

0	0	0	2
5	0	0	0
0	2	0	0
0	0	2	0

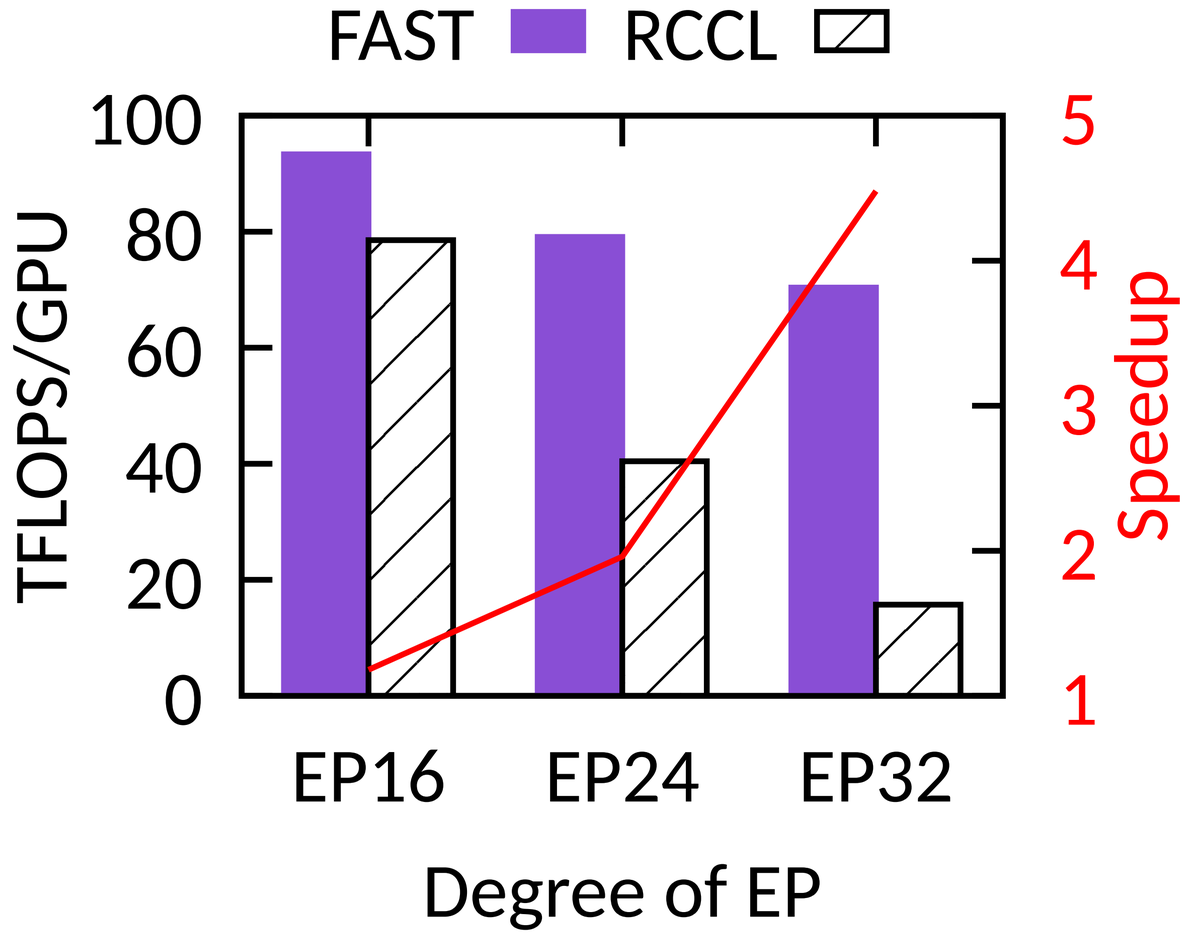
5s

+

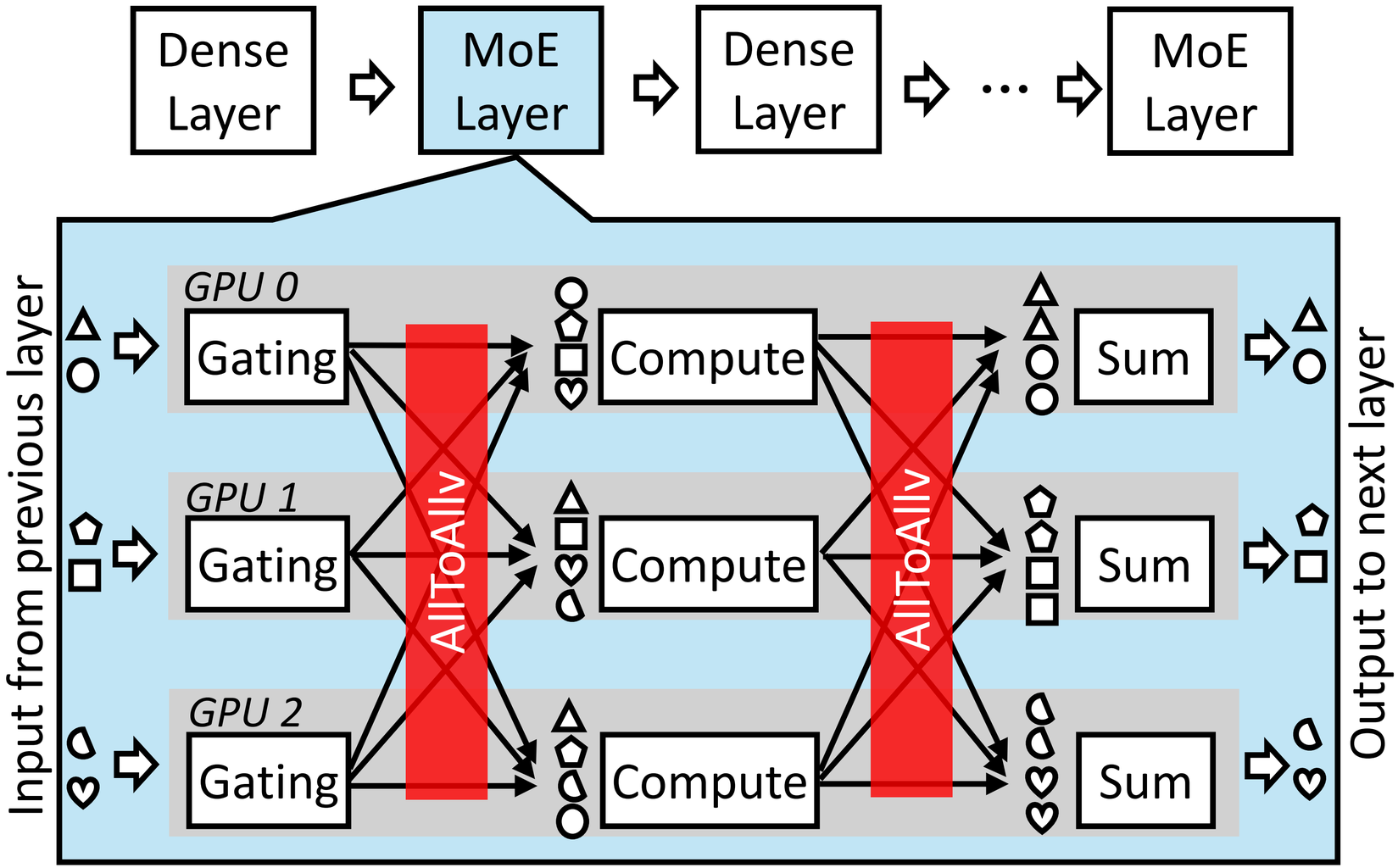
0	0	0	0
0	0	0	0
0	0	0	3
0	0	0	0

3s

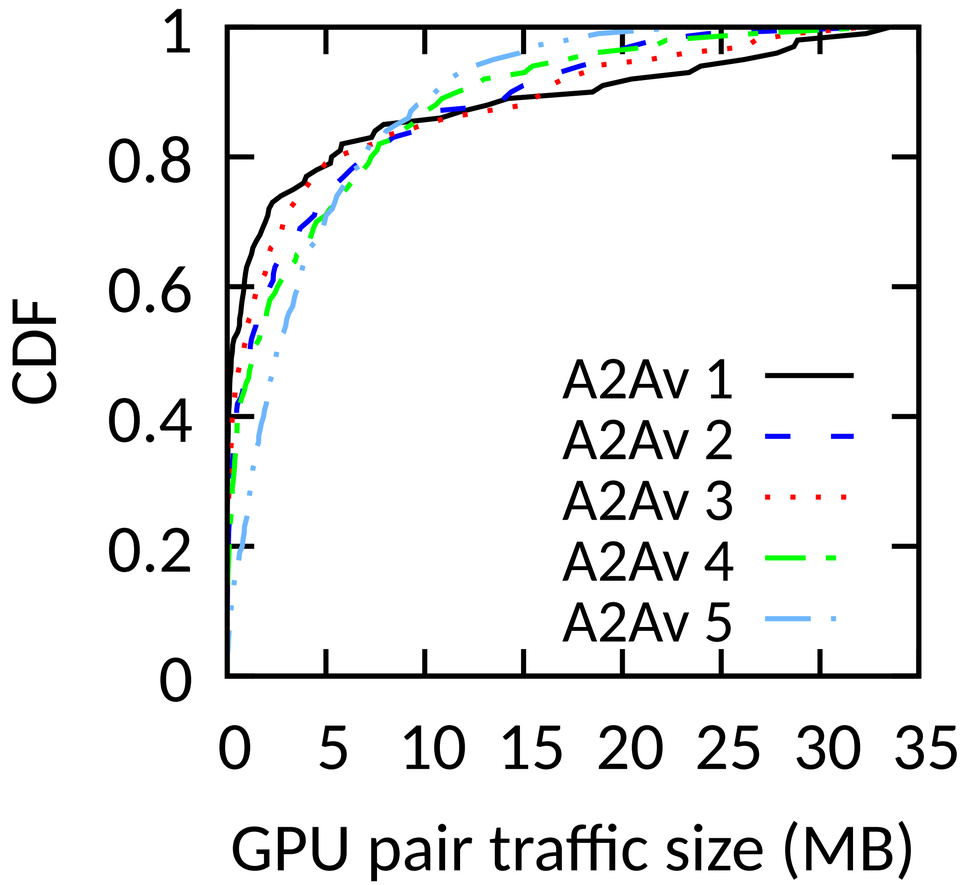
FAST achieves **1.2–4.5x** higher performance when using Megatron-LM to train a MoE model on AMD testbed



All-to-All is heavily used in MoE models



Skew from pretraining a MoE model using Megatron-LM



Dynamism from pretraining a MoE model using Megatron-LM