HARVEST

Adaptive Photonic Switching Schedules for Collective Communication in Scale-up Domains

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PURDUE UNIVERSITY

STyGIANet

Microsoft

NSF

Explosive Growth of Model Sizes

Source: Epoch AI

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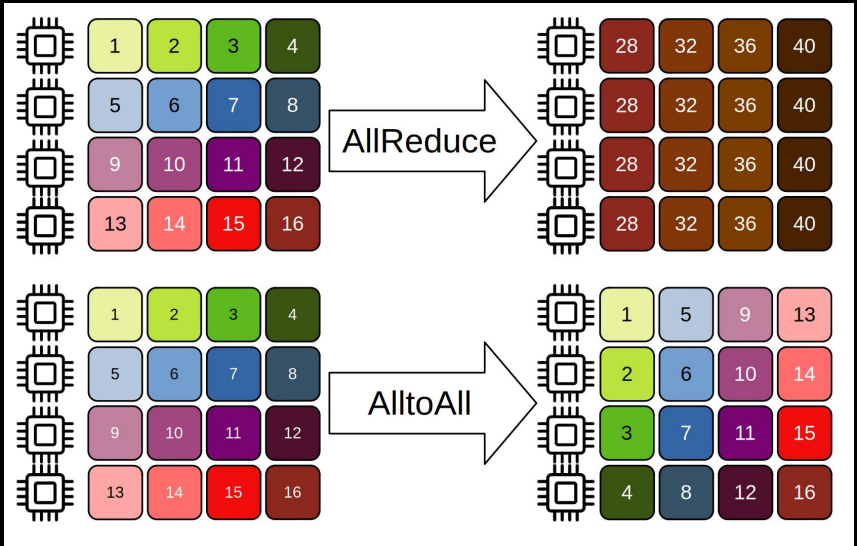
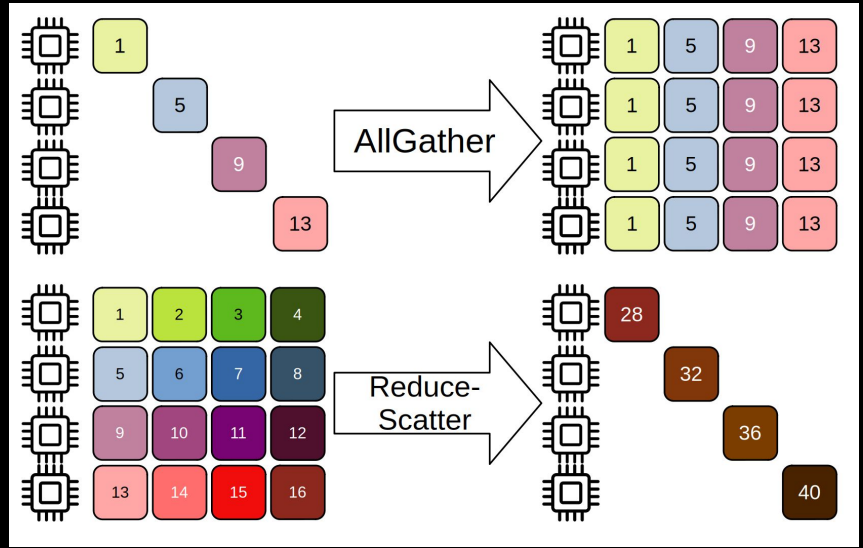
Distributed Computing → Collective Communication





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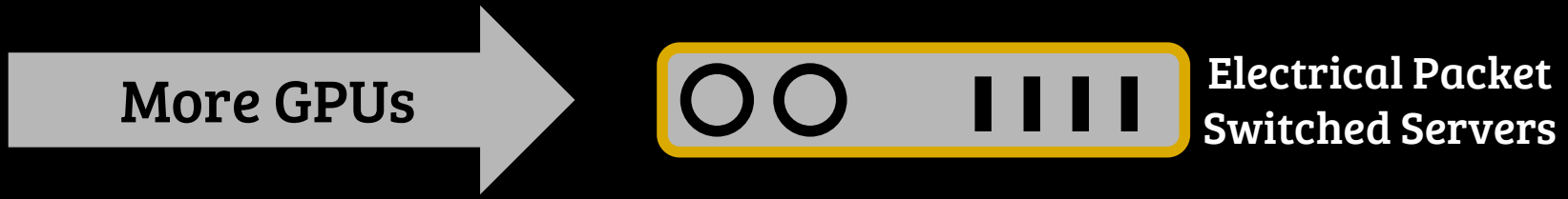
Electrical Interconnects are Hitting their Limits

- Need for more compute resources in our scale-up domains
- However, electrical packet switches face:
  - Limited bandwidth scaling
  - Limited copper reach



Scalable ?

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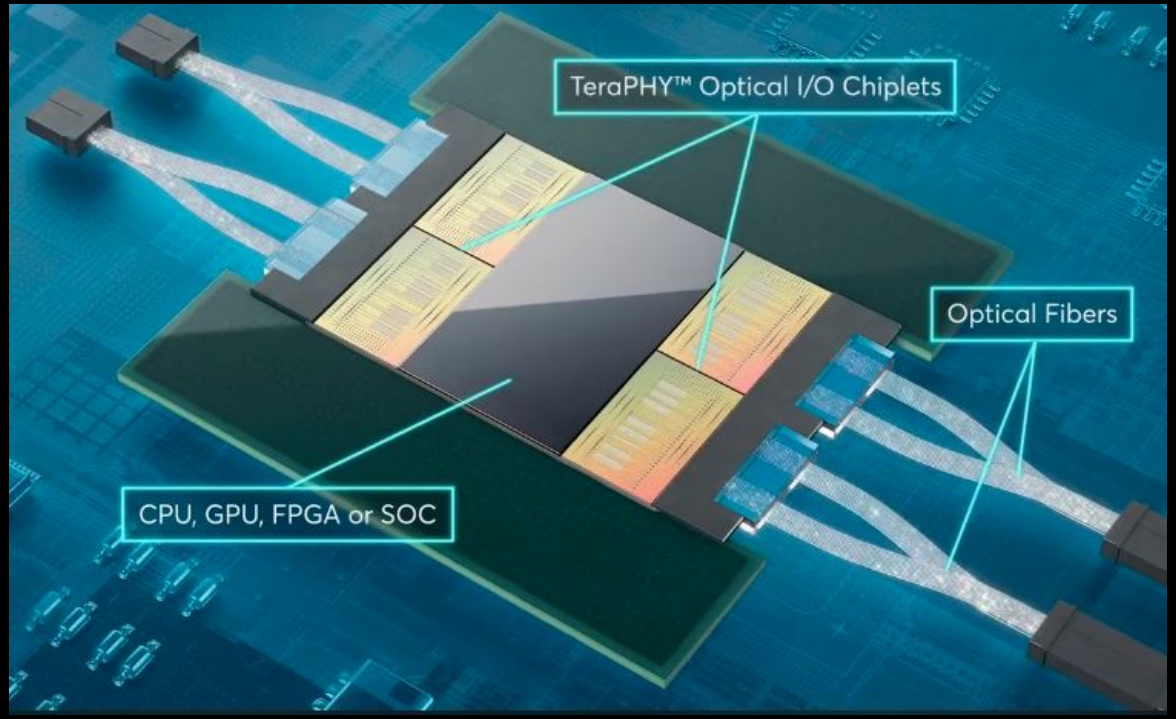
Enter Photonic Interconnects



Source: Ayar Labs

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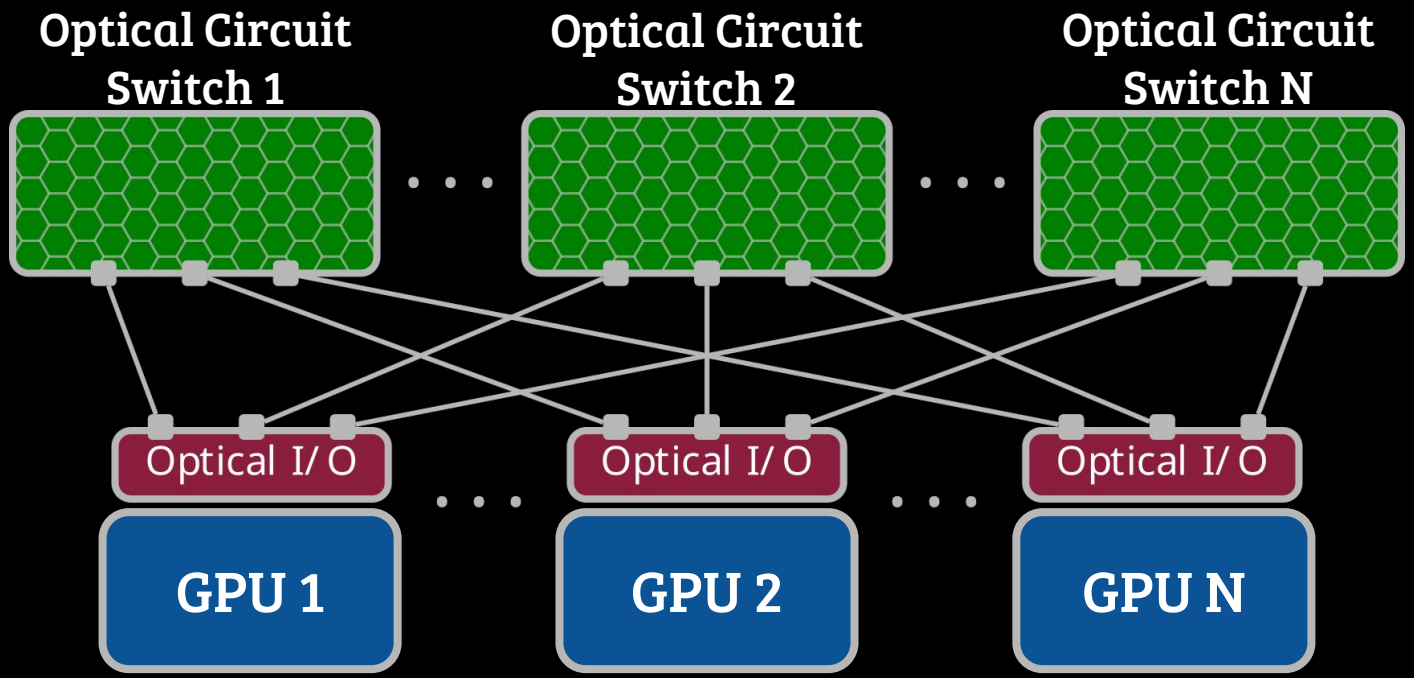
Chip-Chip Photonic Interconnects



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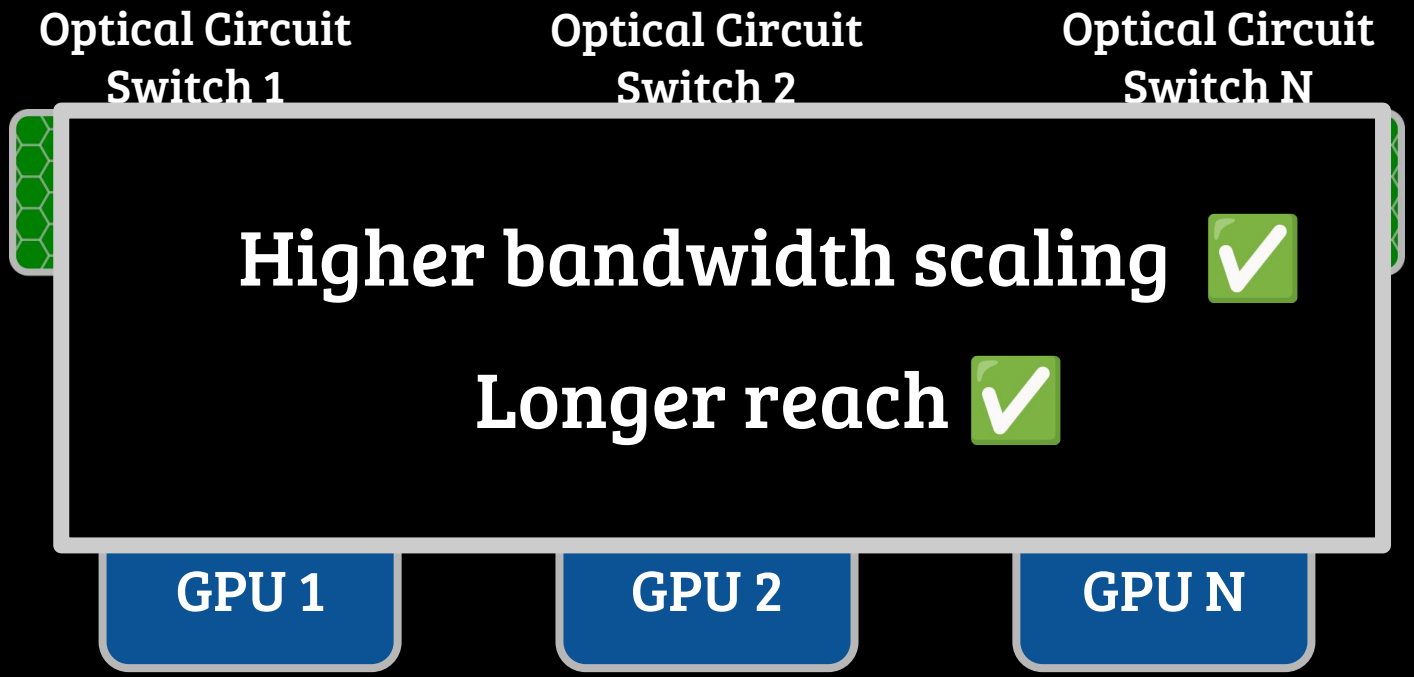
Chip-Chip Photonic Interconnects



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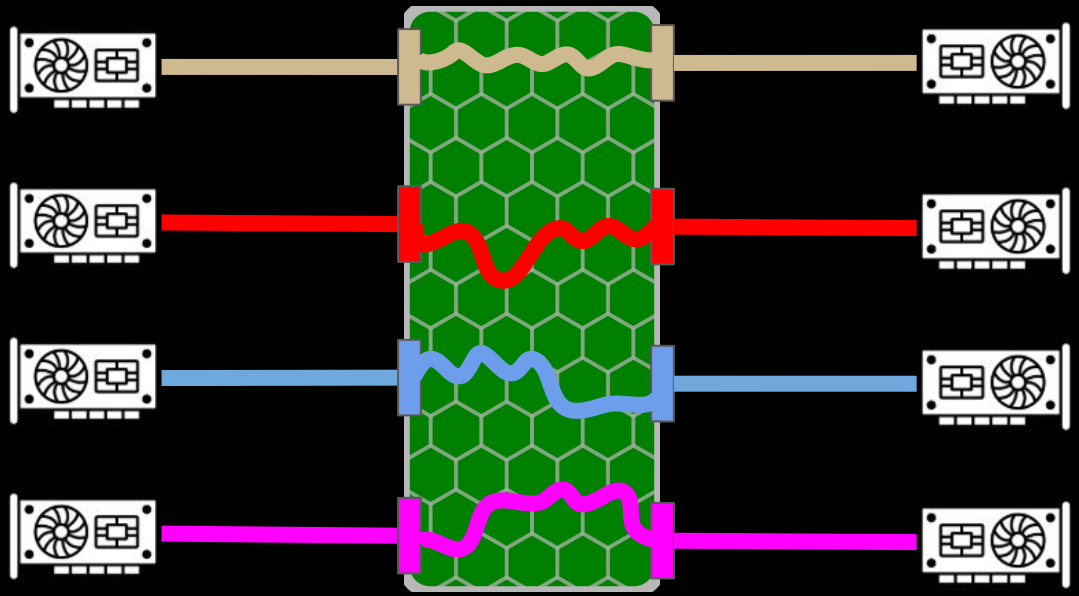
Chip-Chip Photonic Interconnects



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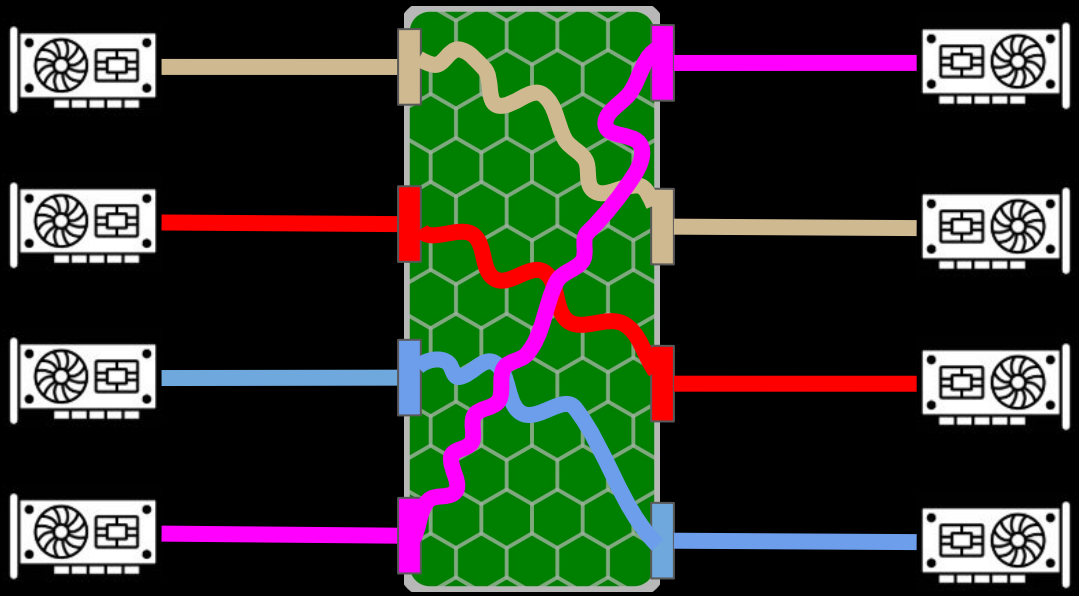
Chip-Chip Photonic Interconnects



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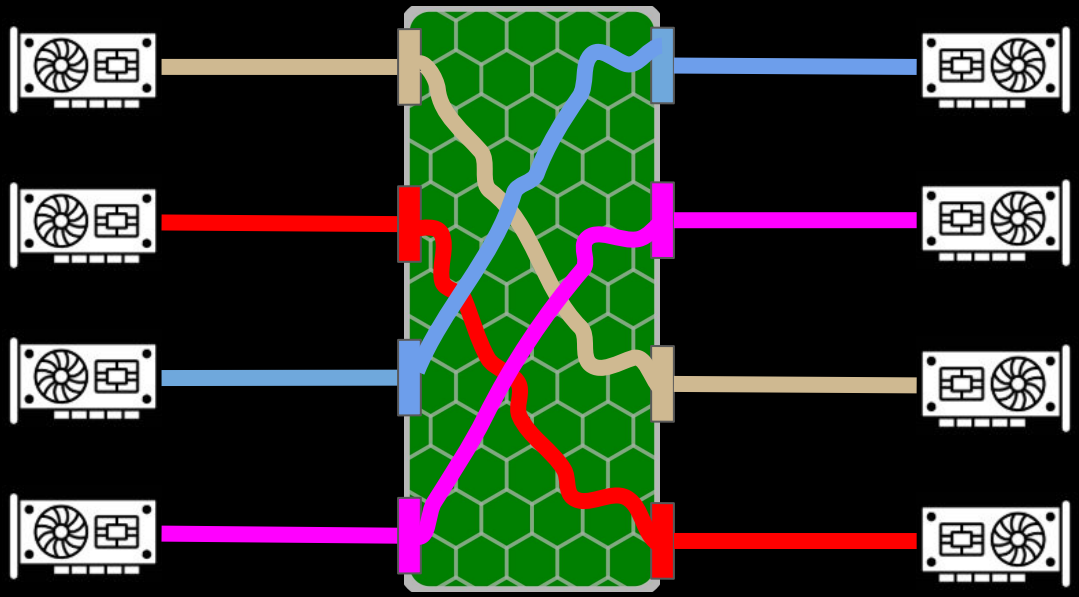
Chip-Chip Photonic Interconnects



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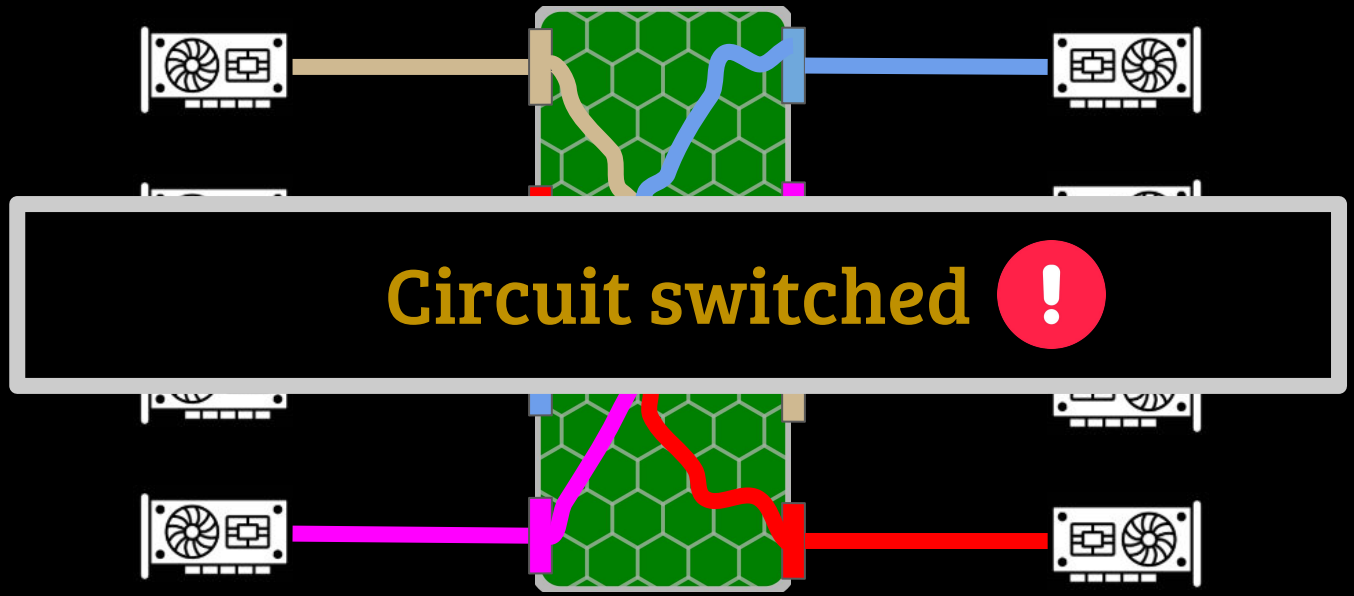
Chip-Chip Photonic Interconnects



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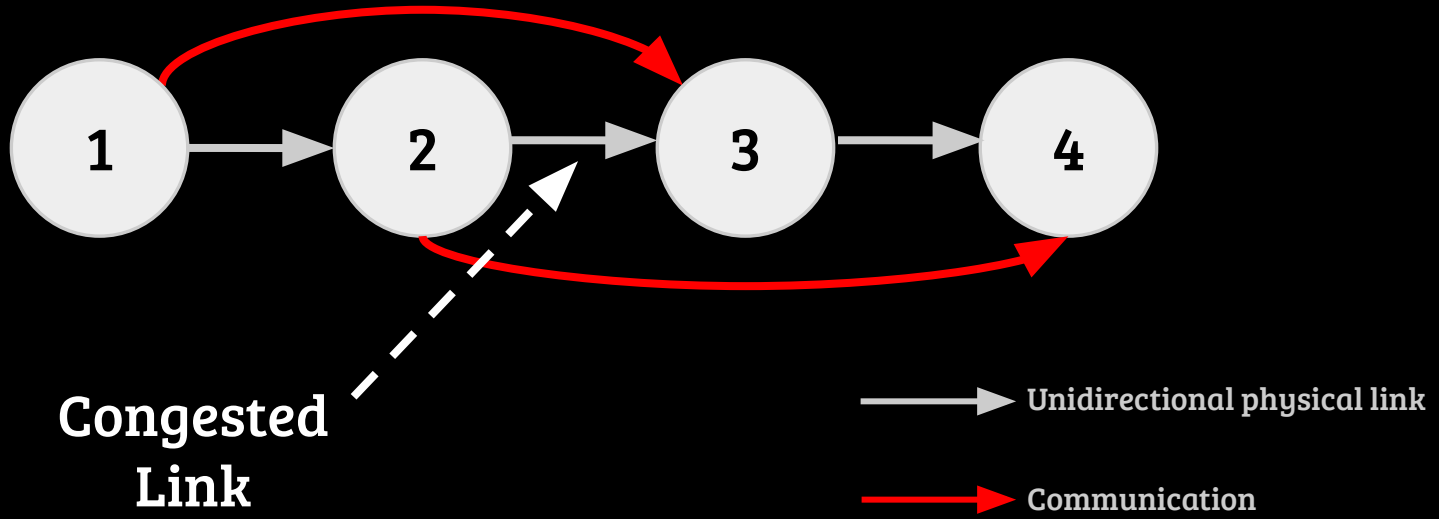
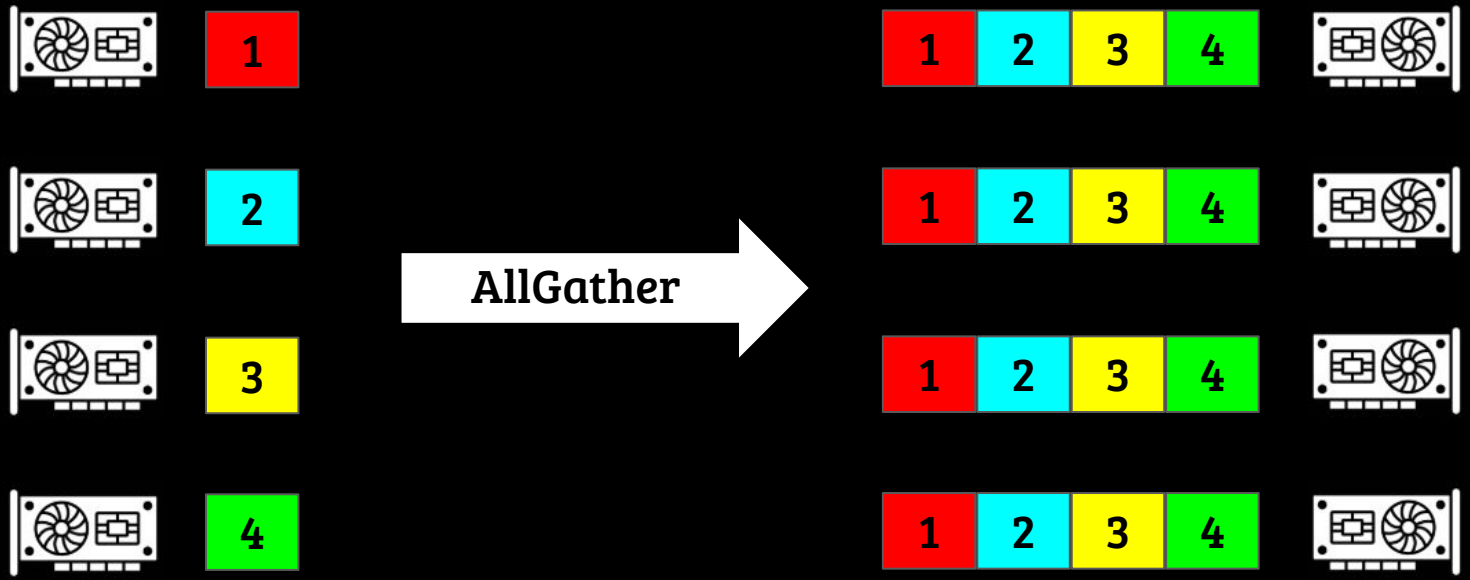
AI Workloads Face New Challenge

- GPU communication is bandwidth intensive and latency sensitive
- Worsens during congestion



Example: AllGather Collective Algorithm

Every GPU transmits distinct chunks of its data to all other GPUs



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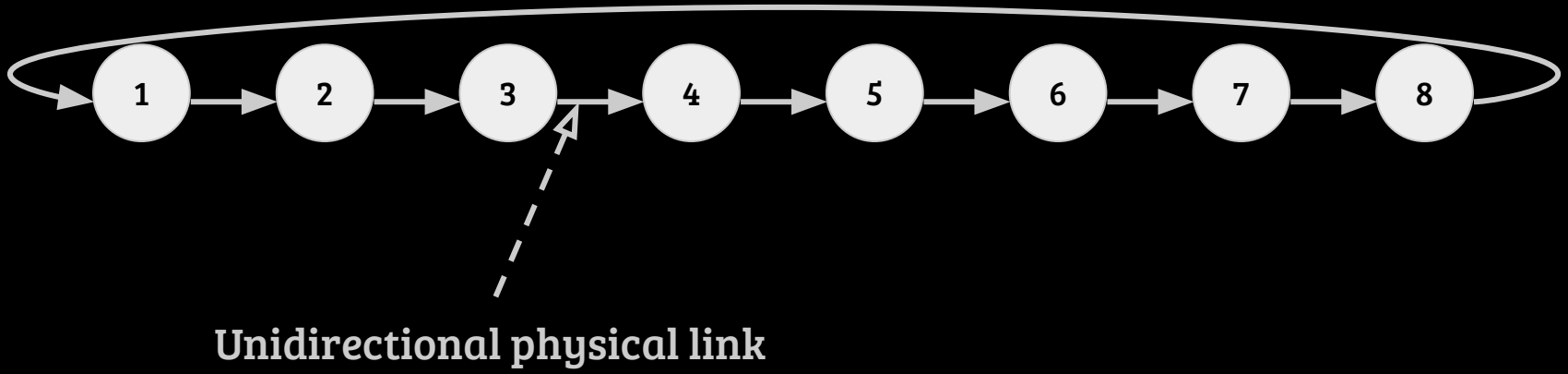
AllGather: Recursive Doubling (Example)

- 8 GPUs connected in a ring topology



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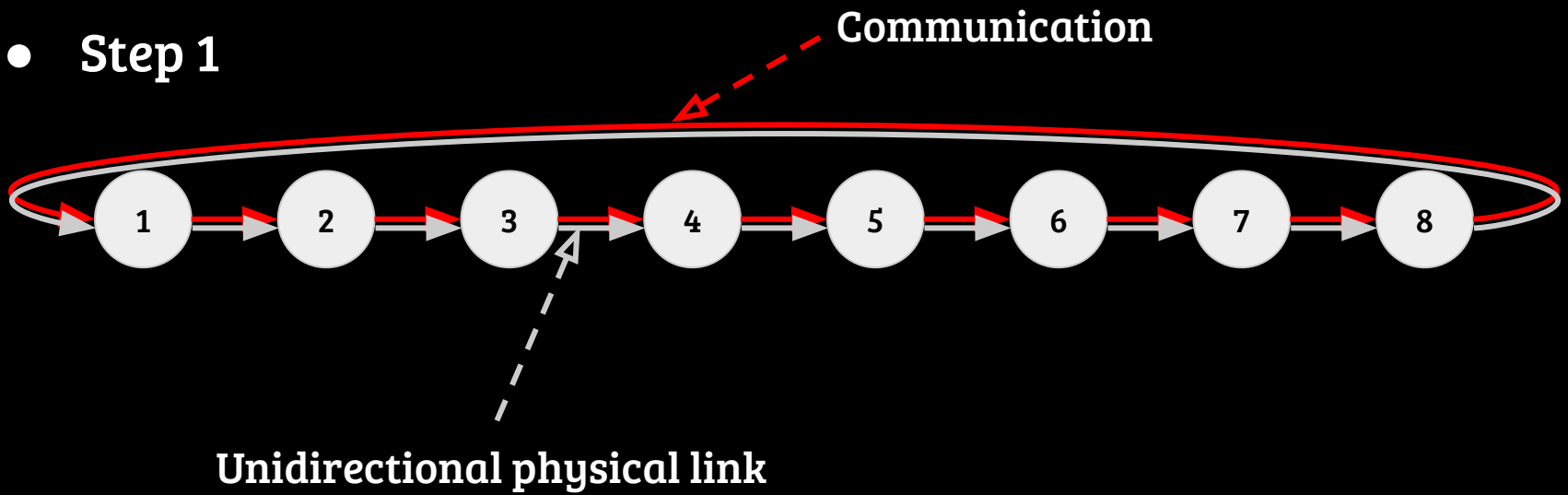
AllGather: Recursive Doubling (Example)

- Step 1



No congestion ✅

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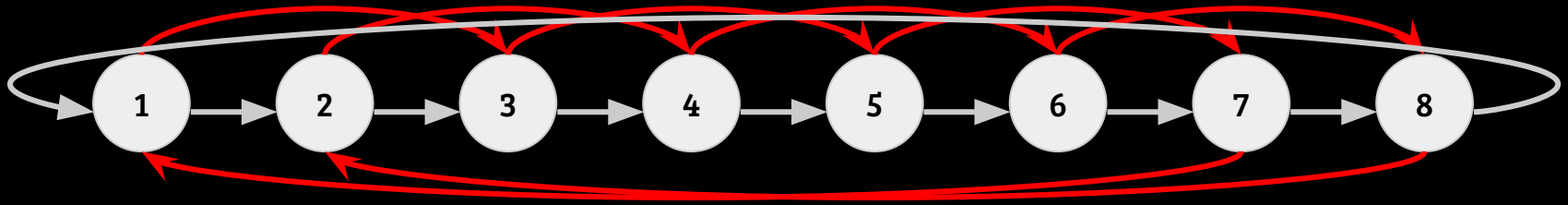
Unidirectional physical link

Communication

AllGather: Recursive Doubling (Example)

- Step 2



Moderate congestion→2 overlapping transfers

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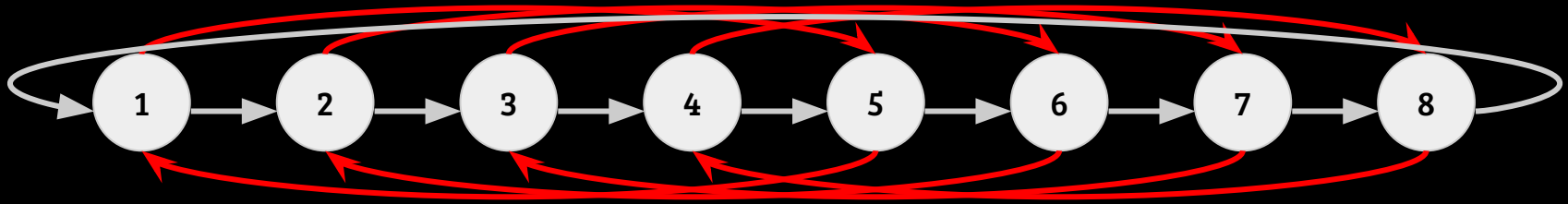
Unidirectional physical link

Communication

AllGather: Recursive Doubling (Example)

- Step 3



Severe congestion→4 overlapping transfers

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An alternative option:

Reconfigure the topology!

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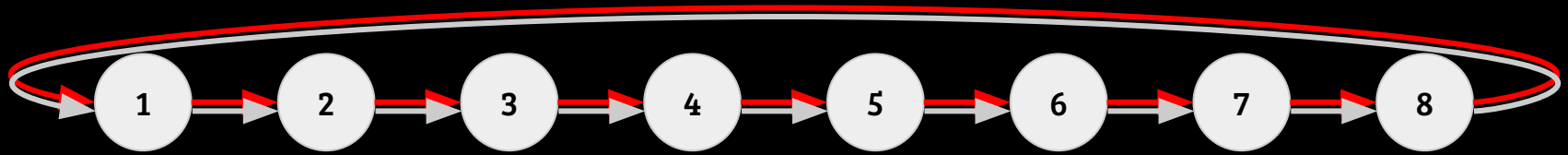
Unidirectional physical link

Communication

AllGather: Recursive Doubling (Example)

- Step 1



No congestion ✅

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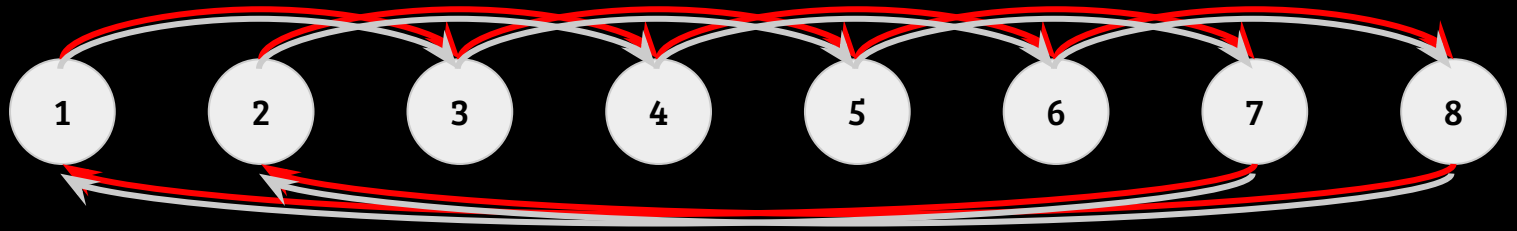
Unidirectional physical link

Communication

AllGather: Recursive Doubling (Example)

- Step 2



Reconfigure! No congestion ✅

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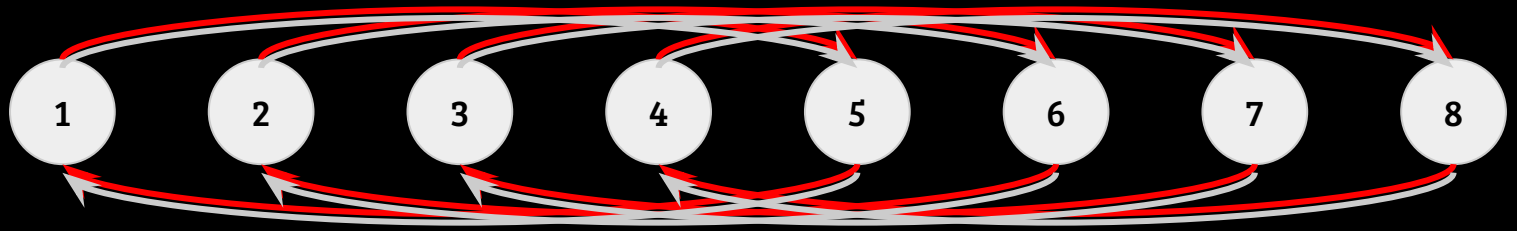
Unidirectional physical link

Communication

AllGather: Recursive Doubling (Example)

- Step 3



Reconfigure and no congestion again! ✅

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Unidirectional physical link

Communication

AllGather: Recursive Doubling (Example)

- Step 3

Different Reconfiguration Schemes

- Periodic circuit switching
- Demand-aware Greedy Matchings
- Failure mitigation
- One-shot optimization
- Aggregate Demand Matrix Decomposition

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Different Reconfiguration Schemes

- Periodic circuit switching
- Demand-aware Greedy Matchings

} **Assumption:** Very low reconfiguration delay

- Failure mitigation
- One-shot optimization

} **Assumption:** Very high reconfiguration delay

- Aggregate Demand Matrix Decomposition

} **Assumption:** No data dependency

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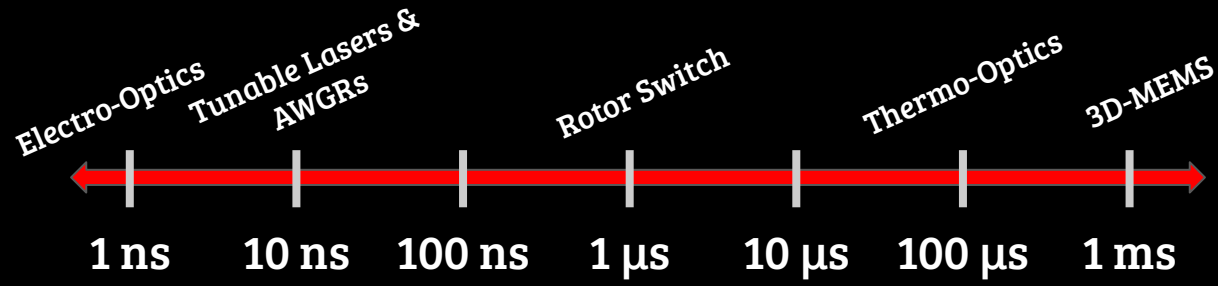
In reality…

- Reconfiguration delays span a wide spectrum
- GPU communication has data dependencies
  - *Aggregate Demand Matrix is not a good abstraction!*



Reconfiguration Delays

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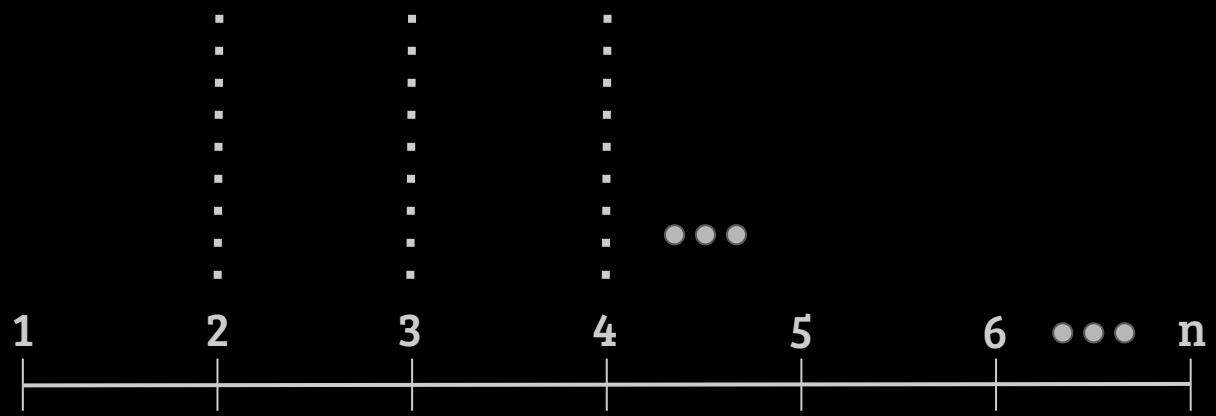
Collective Communication and Completion Time



Communication steps of a collective

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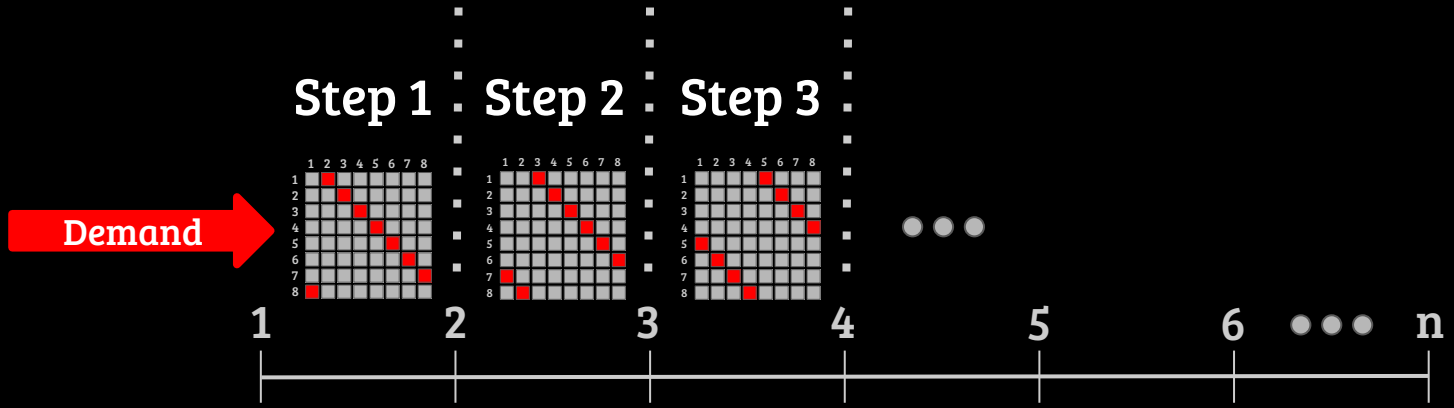
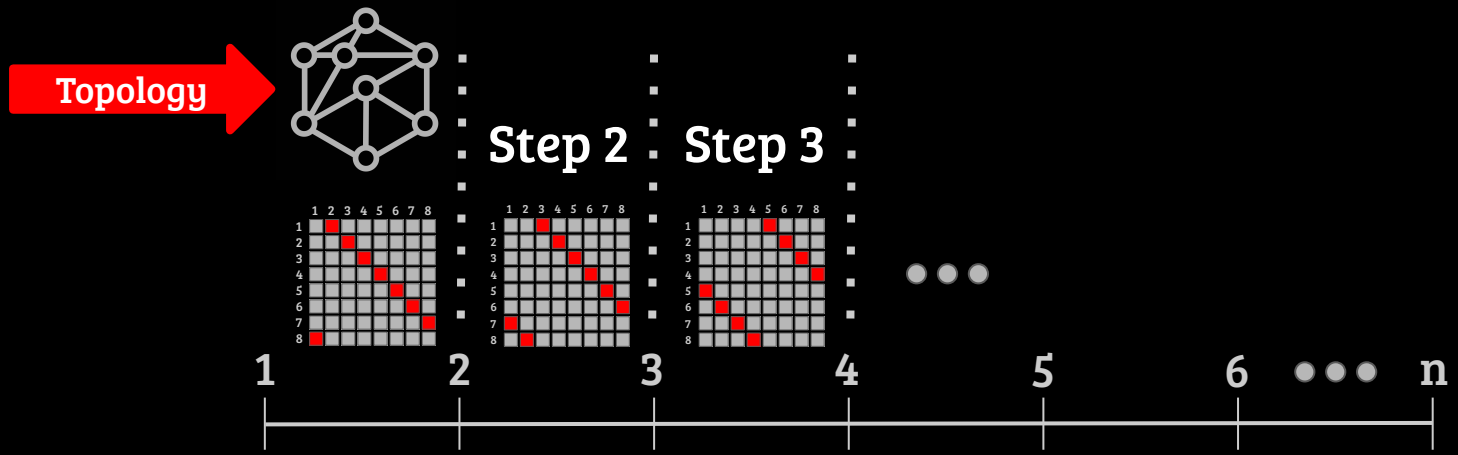
Collective Communication and Completion Time



Communication steps of a collective

Collective Communication and Completion Time



Communication steps of a collective

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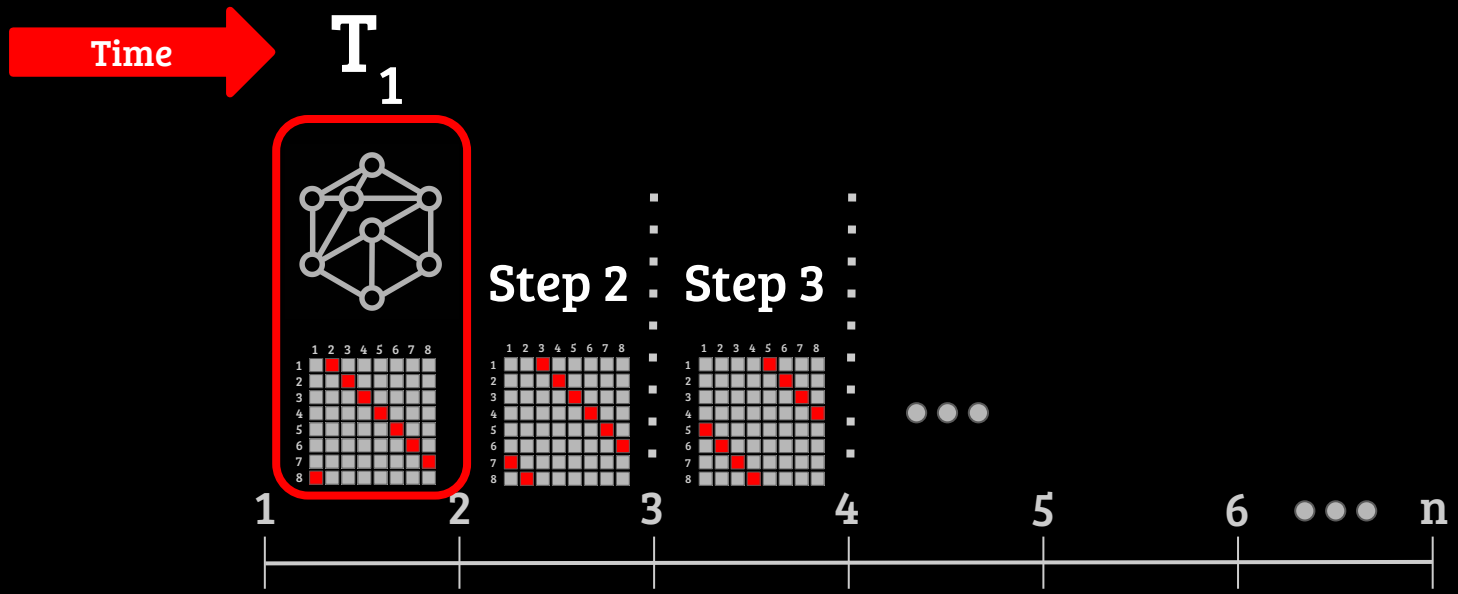
Collective Communication and Completion Time



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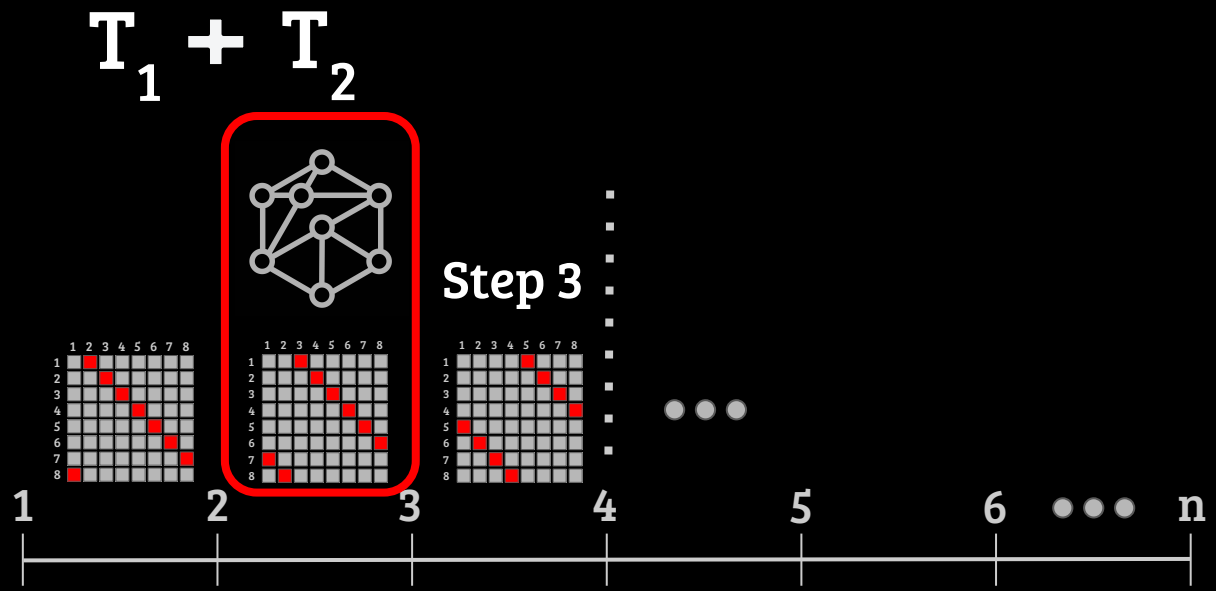
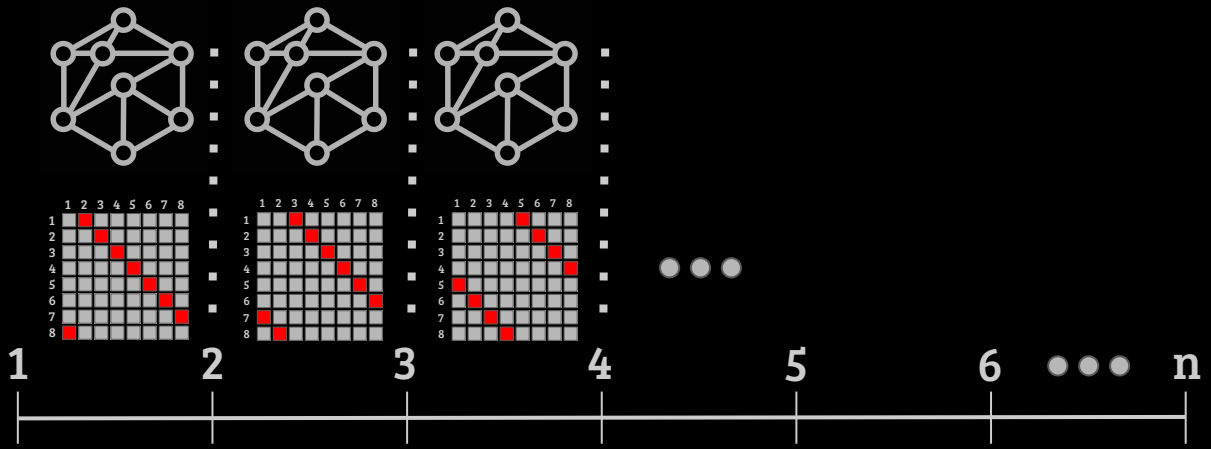
Collective Communication and Completion Time

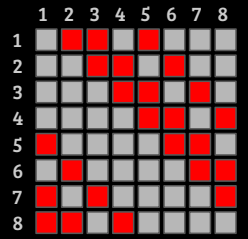


Communication steps of a collective

Collective Communication and Completion Time

$$T_1 + T_2 + T_3 \cdots = \text{Total Collective Completion Time}$$





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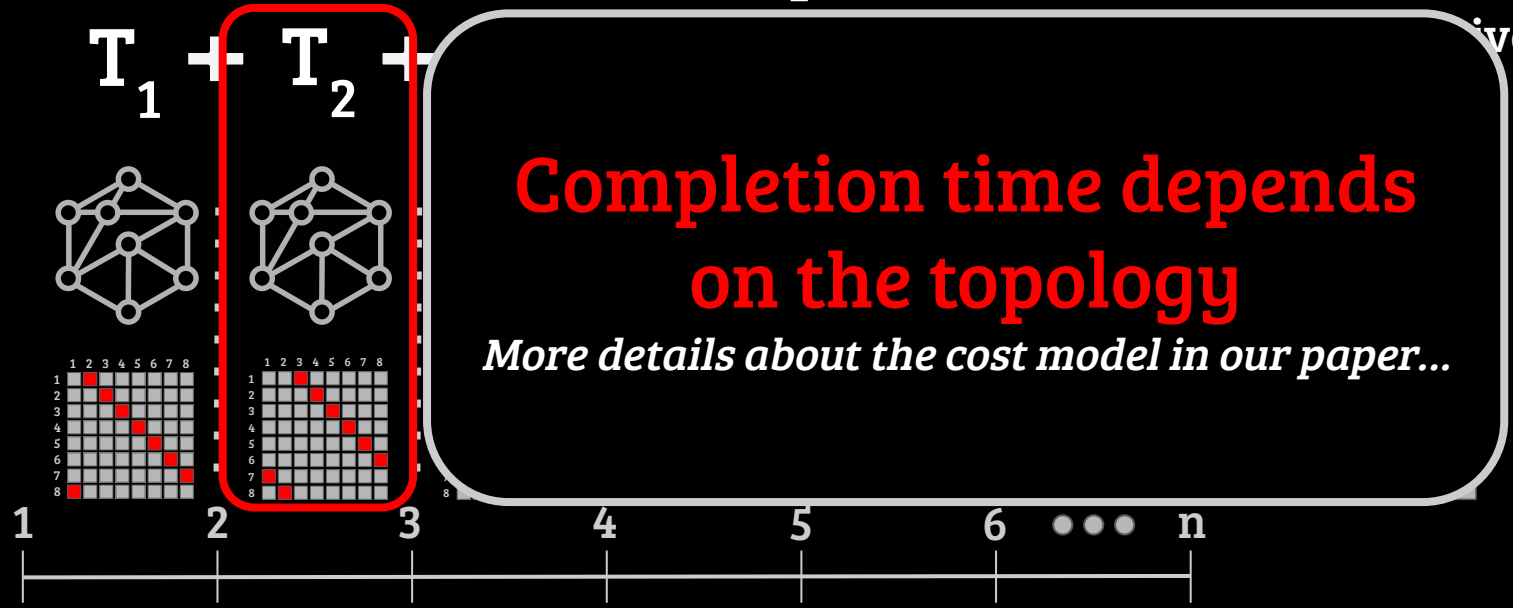
Collective Communication and Completion Time



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An Optimization Opportunity

If we reconfigure:

- Reduced congestion and propagation delays
- Incur reconfiguration delay

Else:

- High congestion and propagation delays
- No reconfiguration delays

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An Optimization Opportunity

Challenge:
When and ***how*** should we reconfigure?

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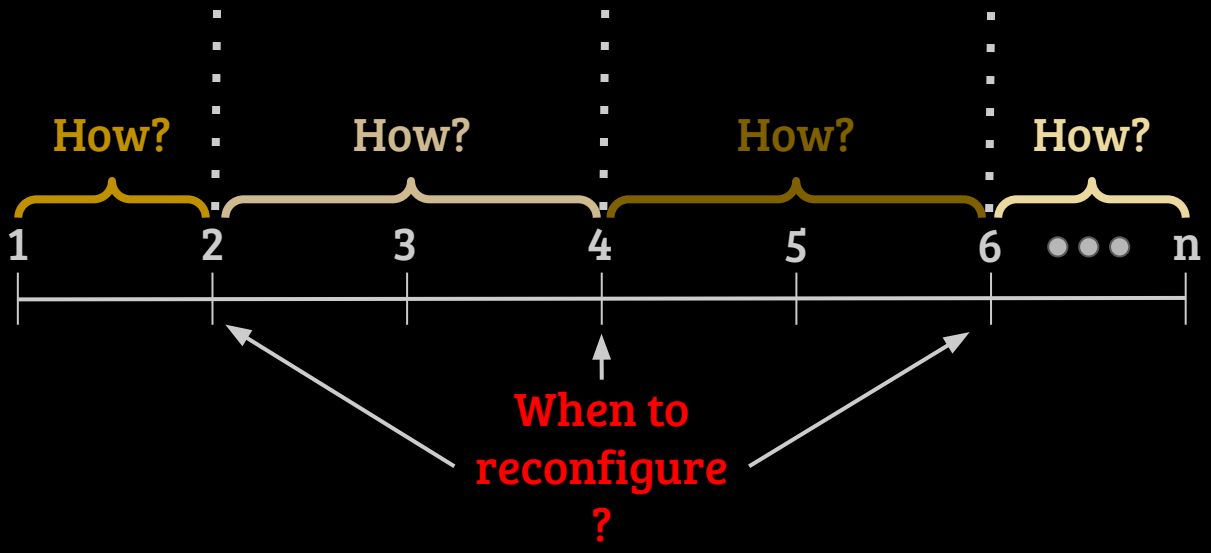
A novel framework that synthesizes optimal photonic switching schedules for collective algorithms

Collective Algorithm
Topology Constraints (# of links, nodes, etc.)
Reconfiguration Delay

Topology
Reconfiguration
Schedule

When and How to Reconfigure?

1. When? Partition the sequence of communication steps into intervals
2. How? Find an optimal static topology for each interval



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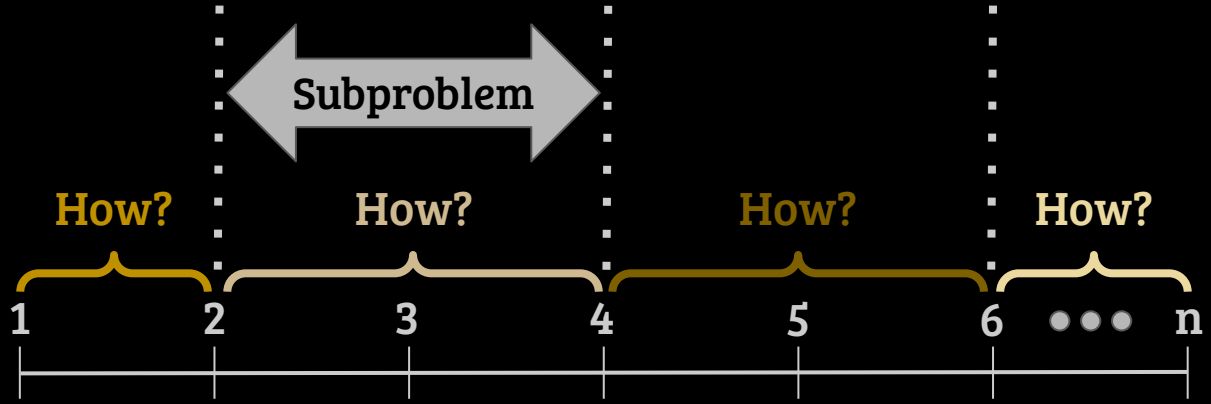
When and How to Reconfigure?



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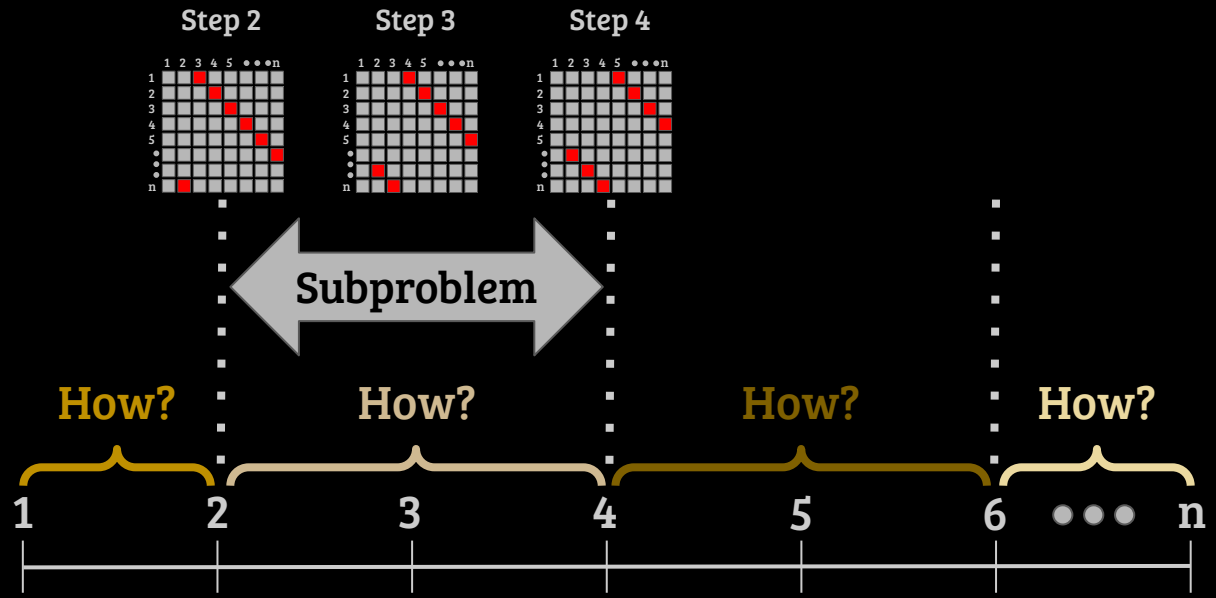
When and How to Reconfigure?



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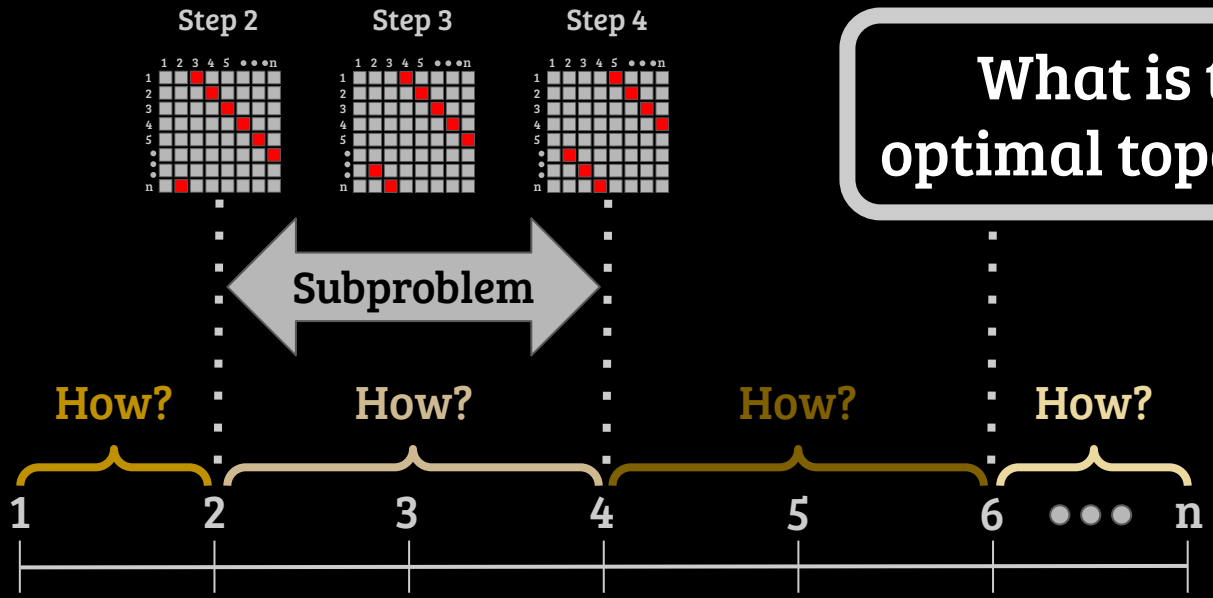

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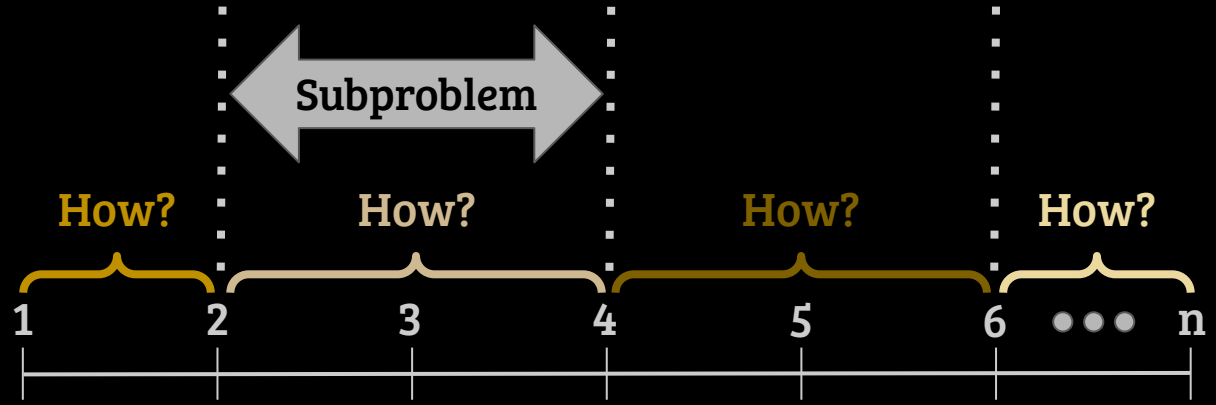
When and How to Reconfigure?

Mixed Integer Second Order Conic Problem



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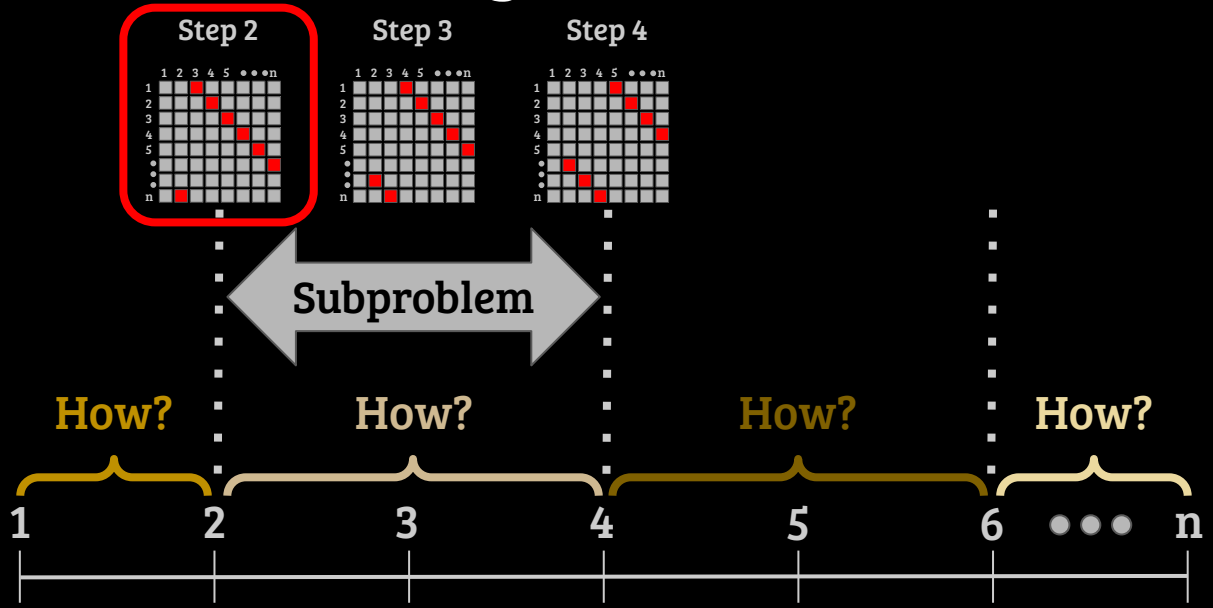

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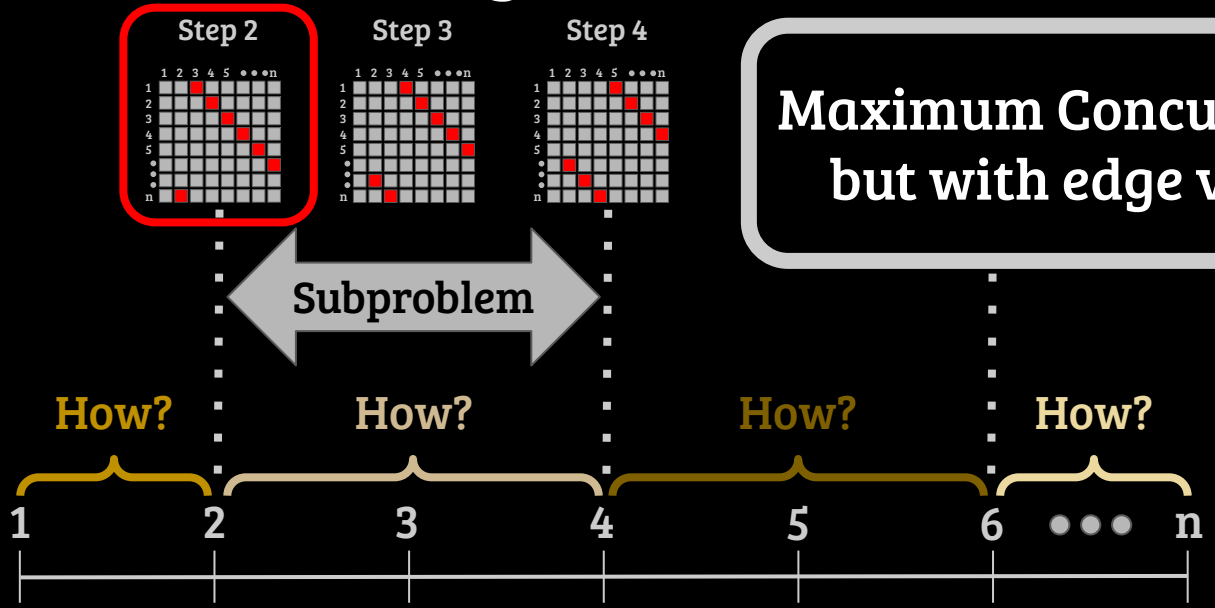

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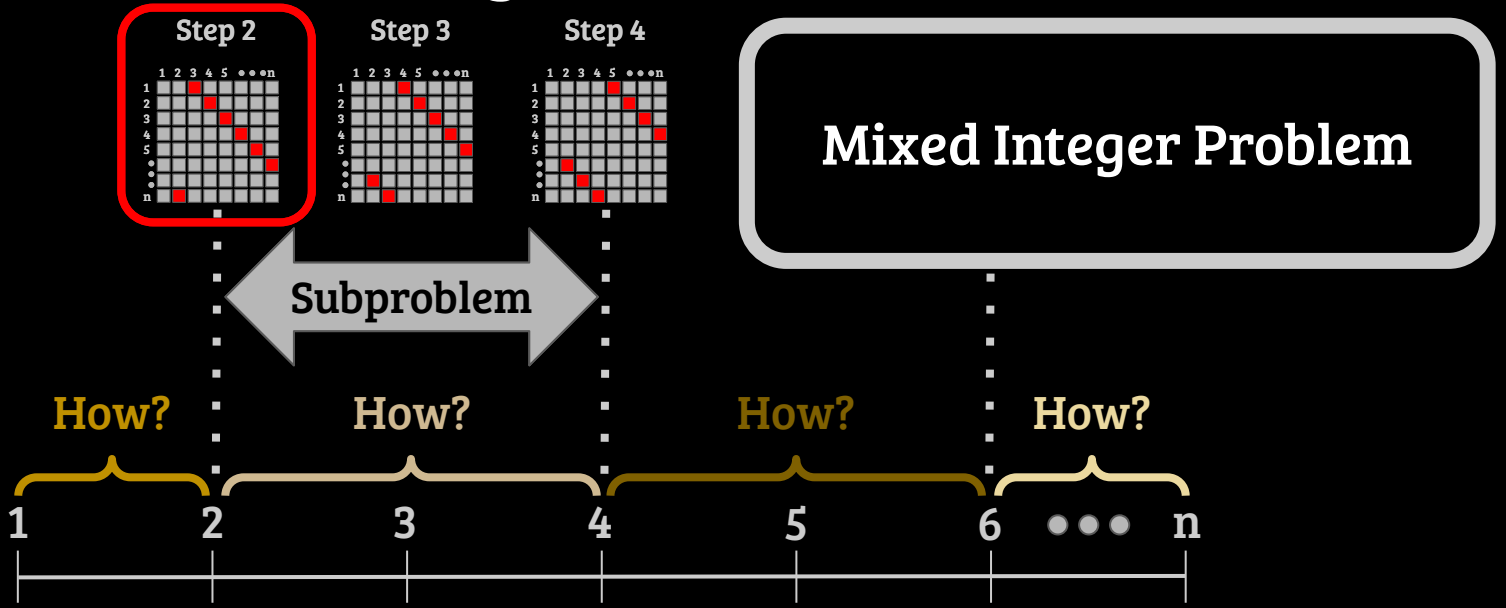

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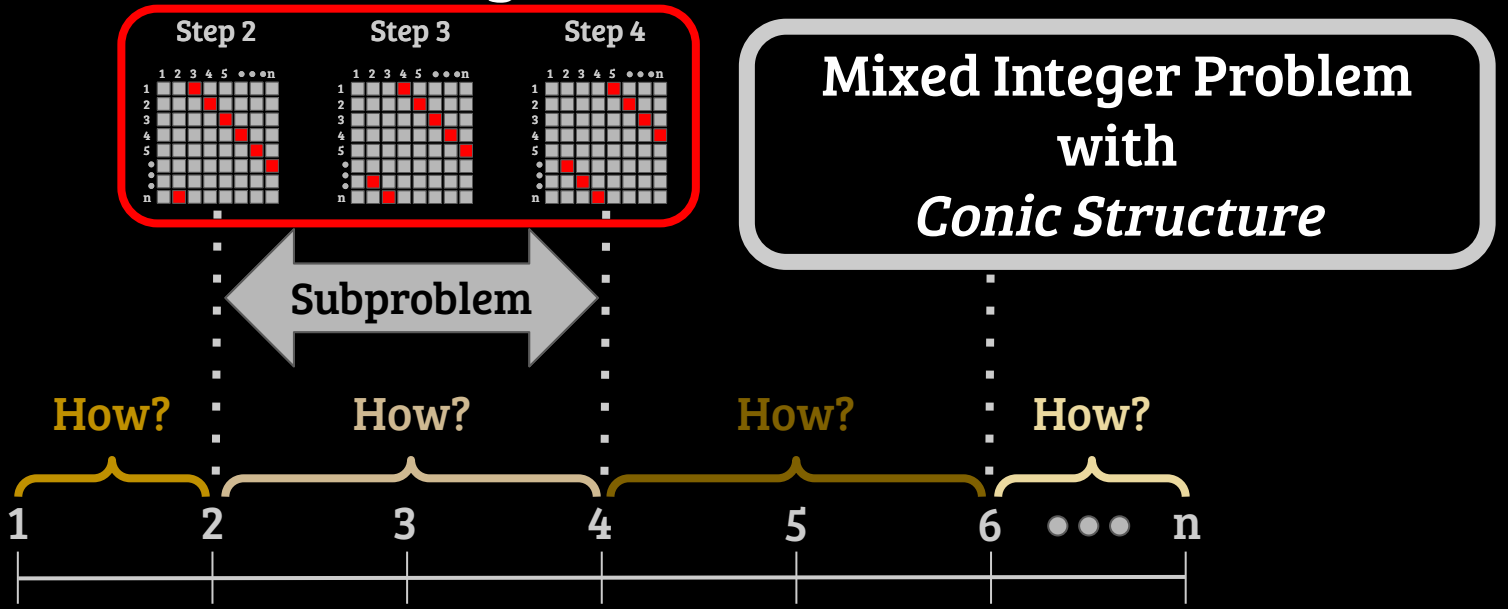

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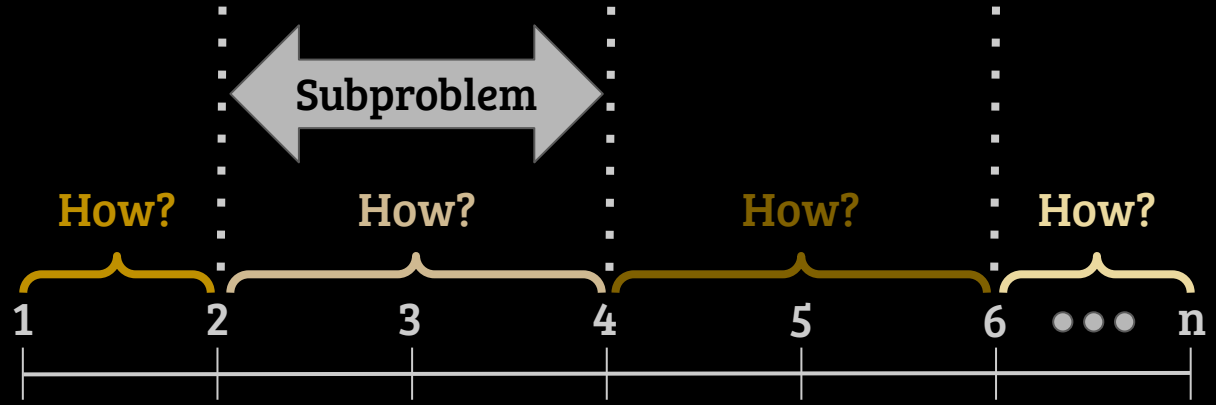
When and How to Reconfigure?

Mixed Integer Second Order Conic Problem



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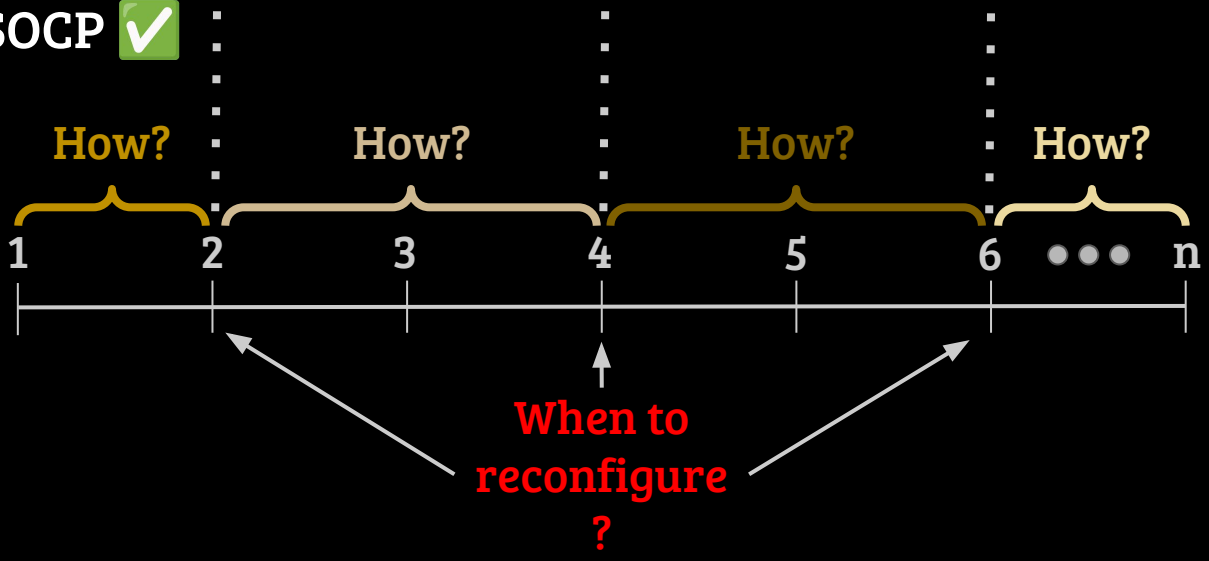
When and How to Reconfigure?

1. When? Partition the sequence of communication steps into intervals
2. ~~How? Find an optimal static topology for each interval~~
   a. MISOCP ✅



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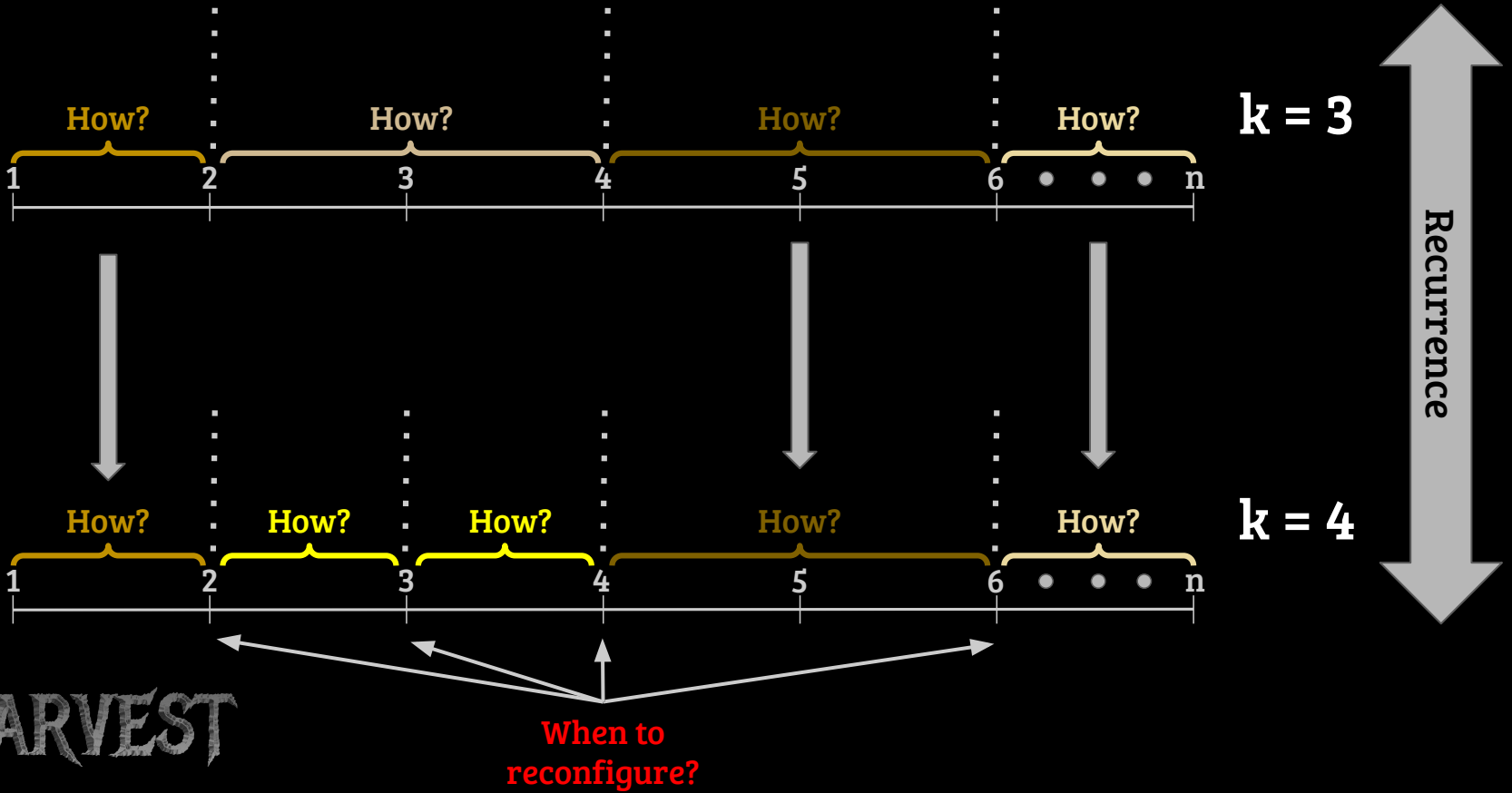
k -> number of reconfigurations

When and How to Reconfigure?



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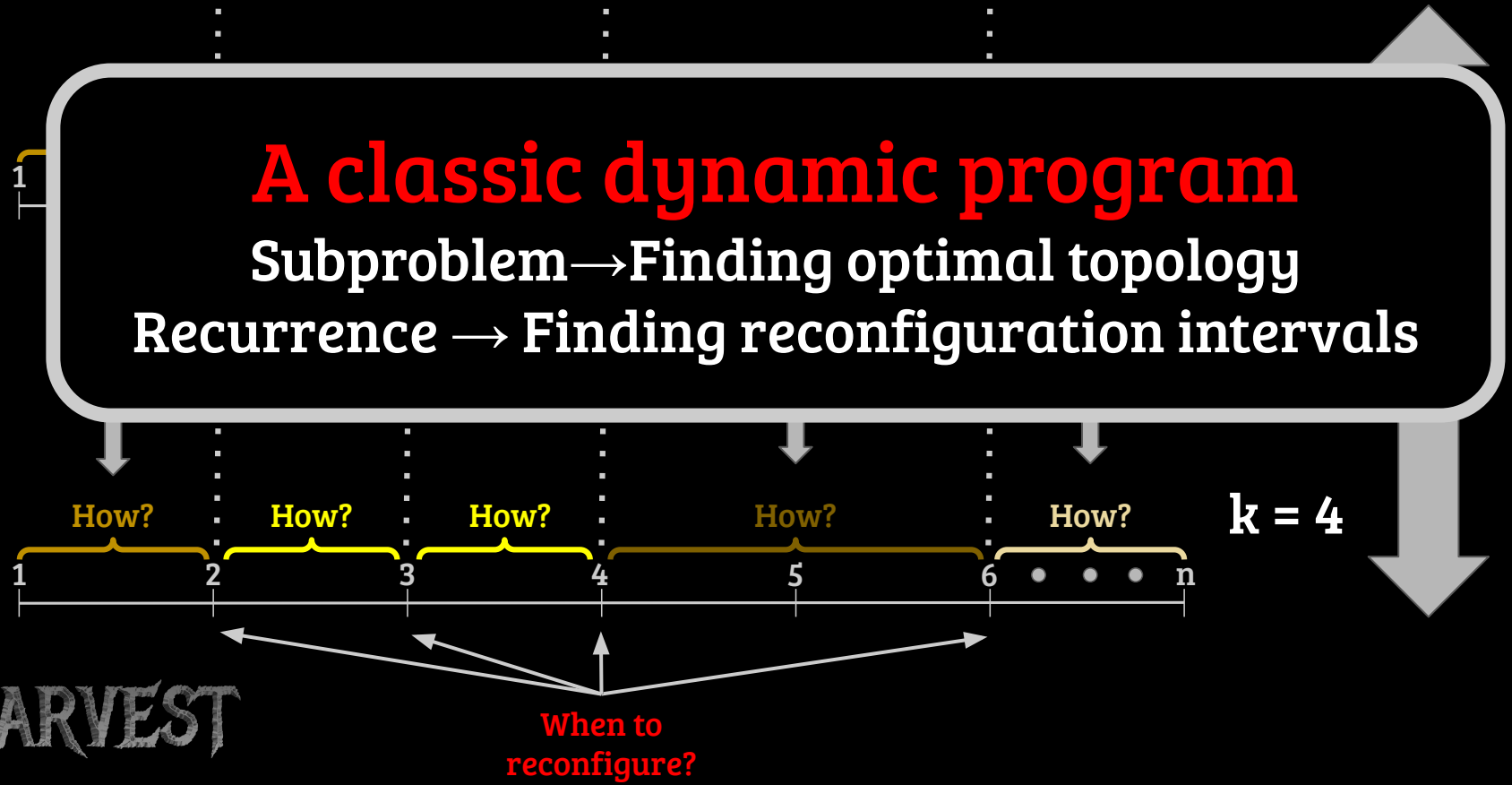
When and How to Reconfigure?



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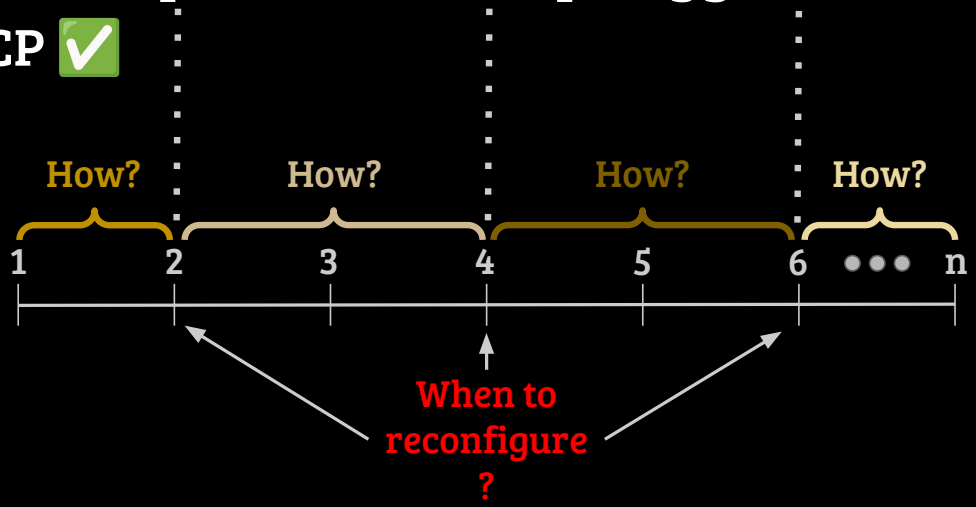
When and How to Reconfigure?

1. ~~When? Partition the sequence of communication steps into intervals~~
   a. Dynamic programming ✅
2. ~~How? Find an optimal static topology for each interval~~
   a. MISOCP ✅



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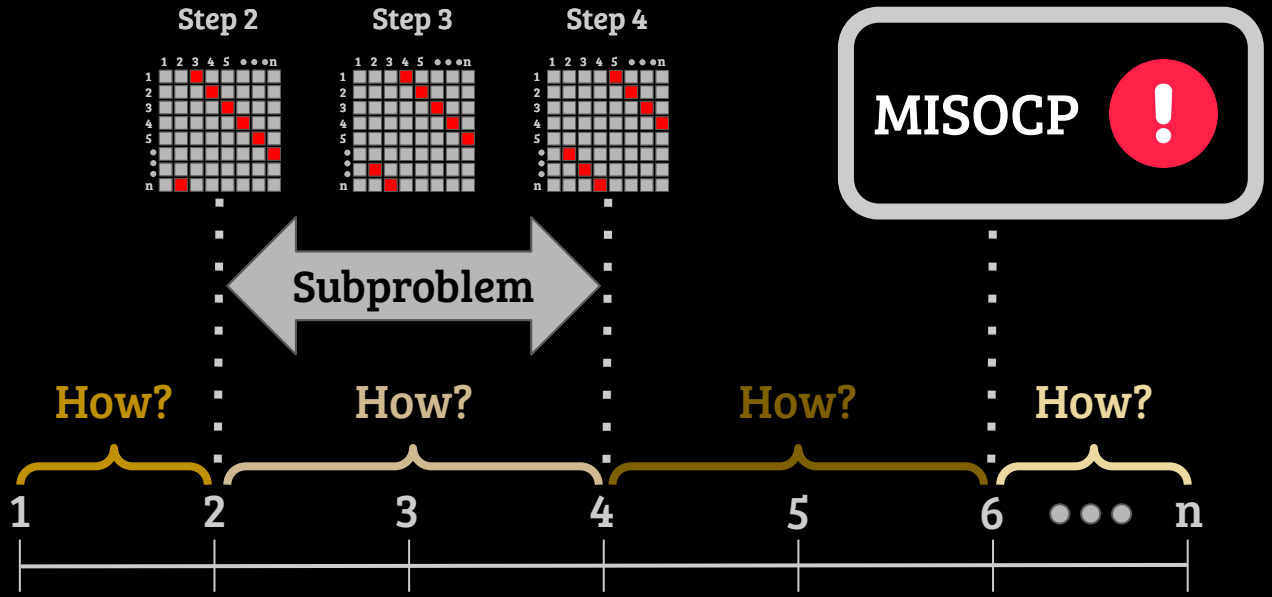

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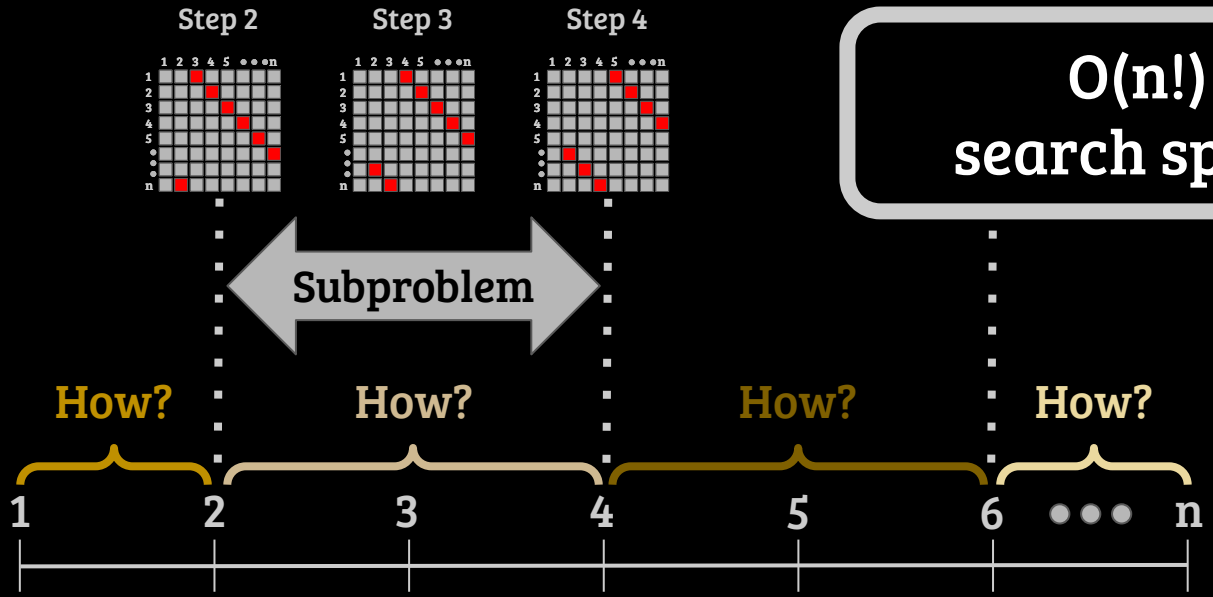

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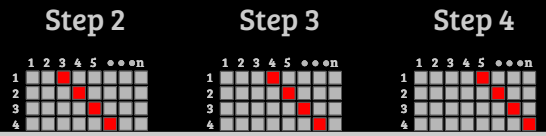
When and How to Reconfigure?



Can we reduce the search space without compromising optimality?

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When and How to Reconfigure?

- Collectives with geometric distance progression
  node *i* communicates with node $i + d^k$ in step *k*
  - Recursive doubling: d = 2
  - Bruck's All-to-All and AllReduce: d = 3, 4, …, r
  - Hypercube All-to-All: d = 2
  - Trivance: d = 3

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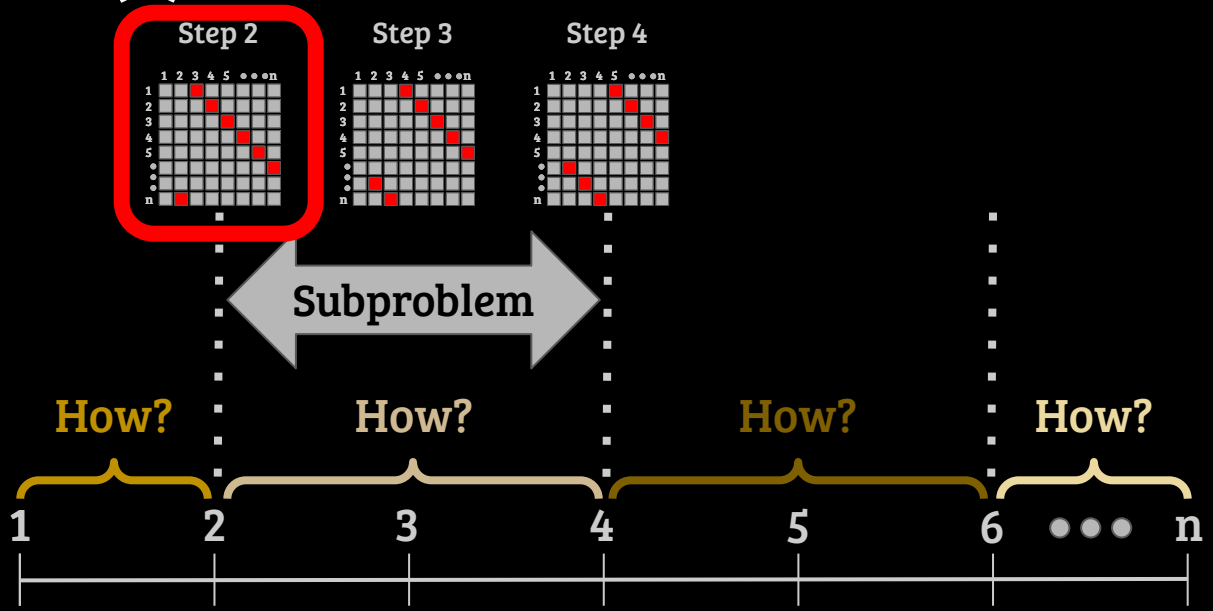
Observation (3)



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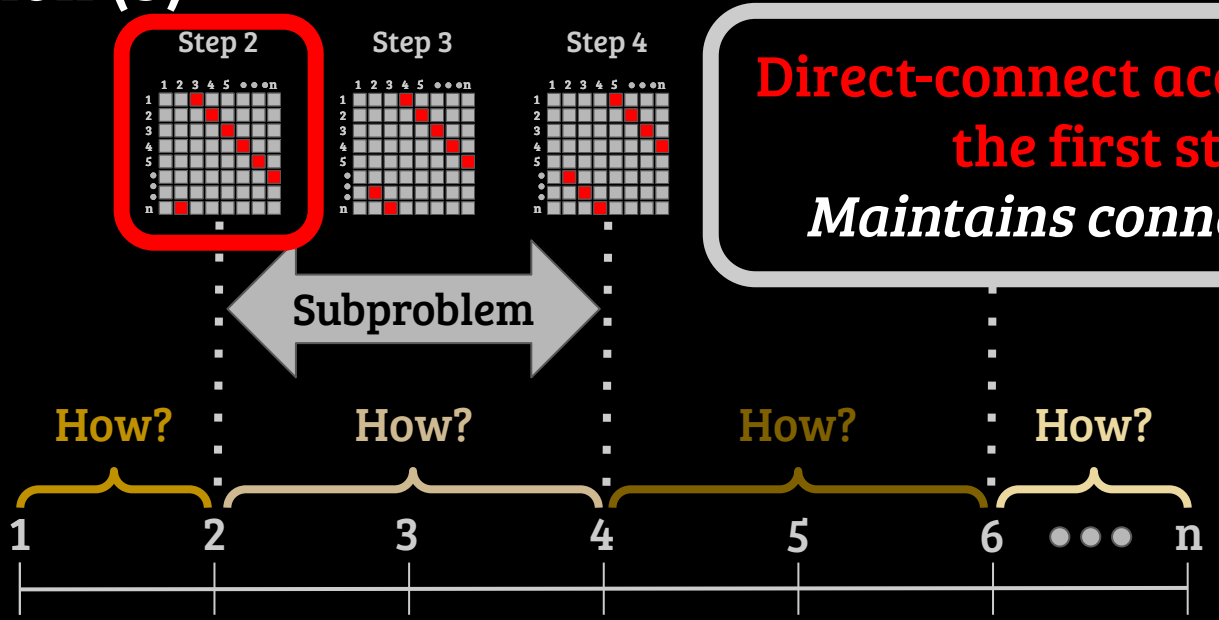
Observation (3)



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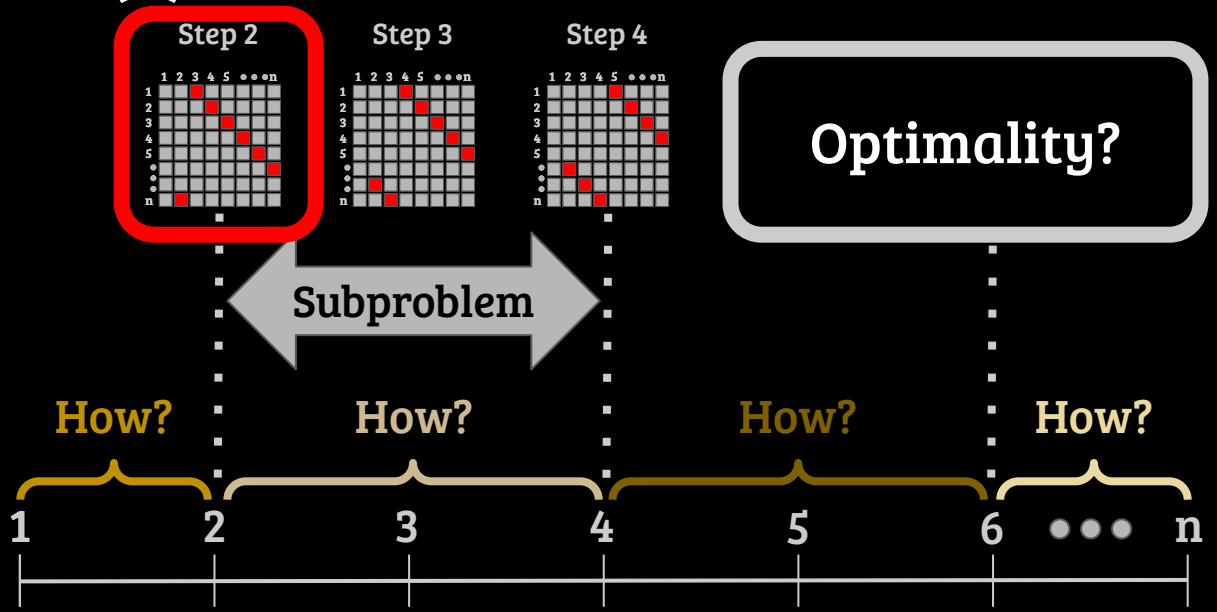
Observation (4)



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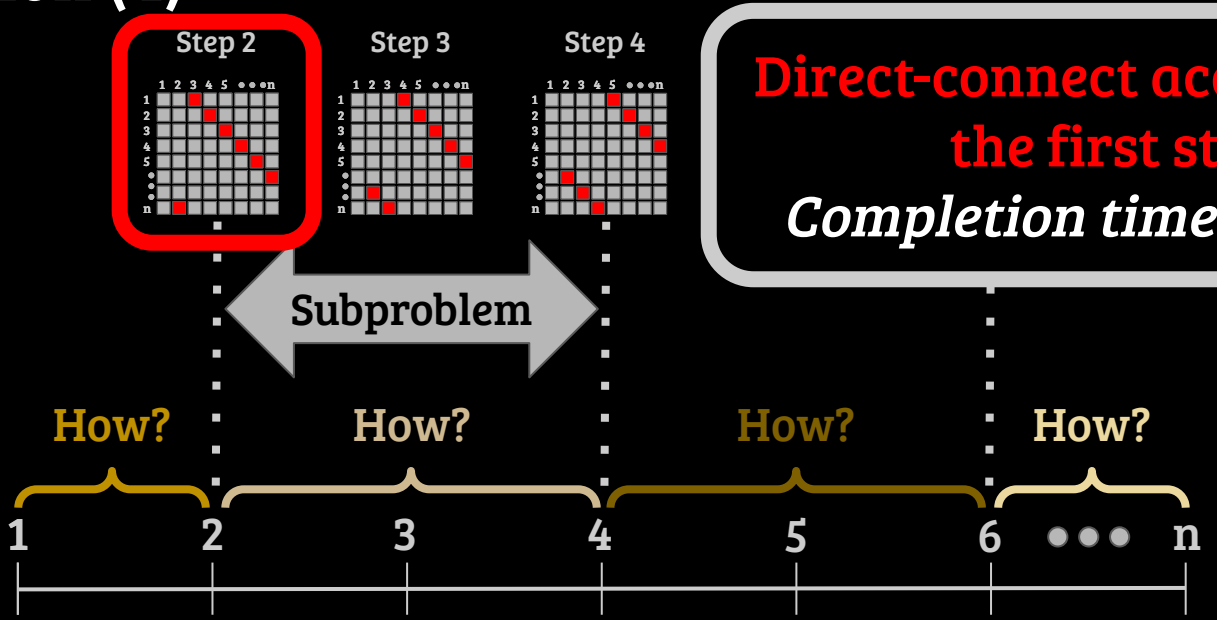
Observation (4)

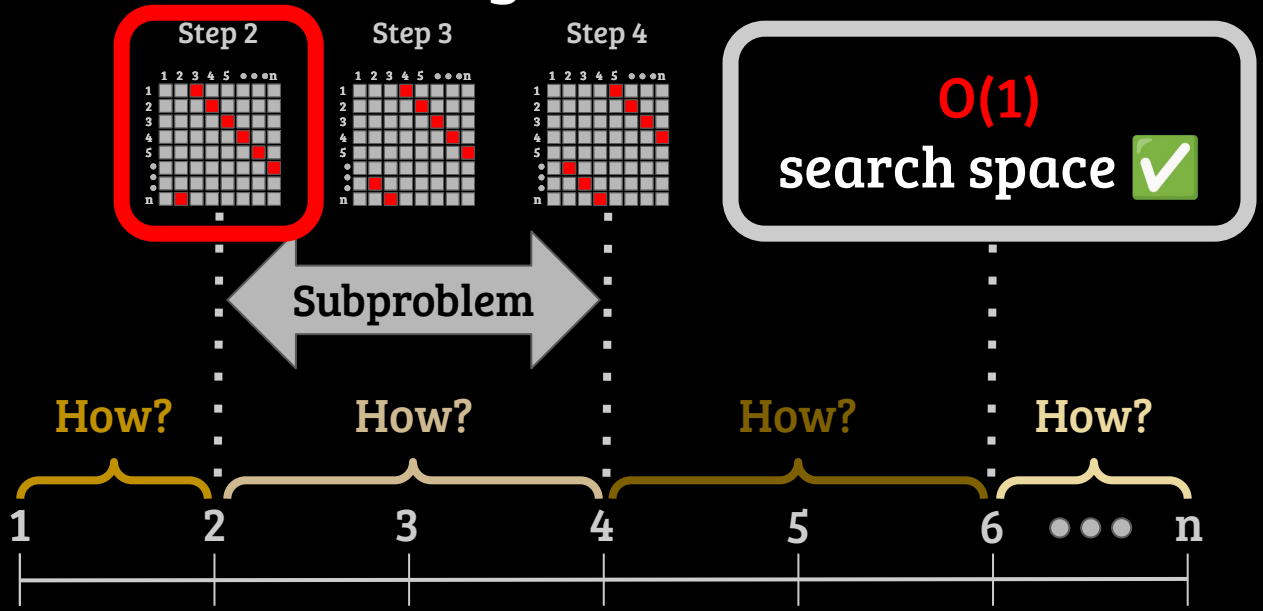


Direct-connect according to the first step

Completion time optimal!

HARVEST

When and How to Reconfigure?



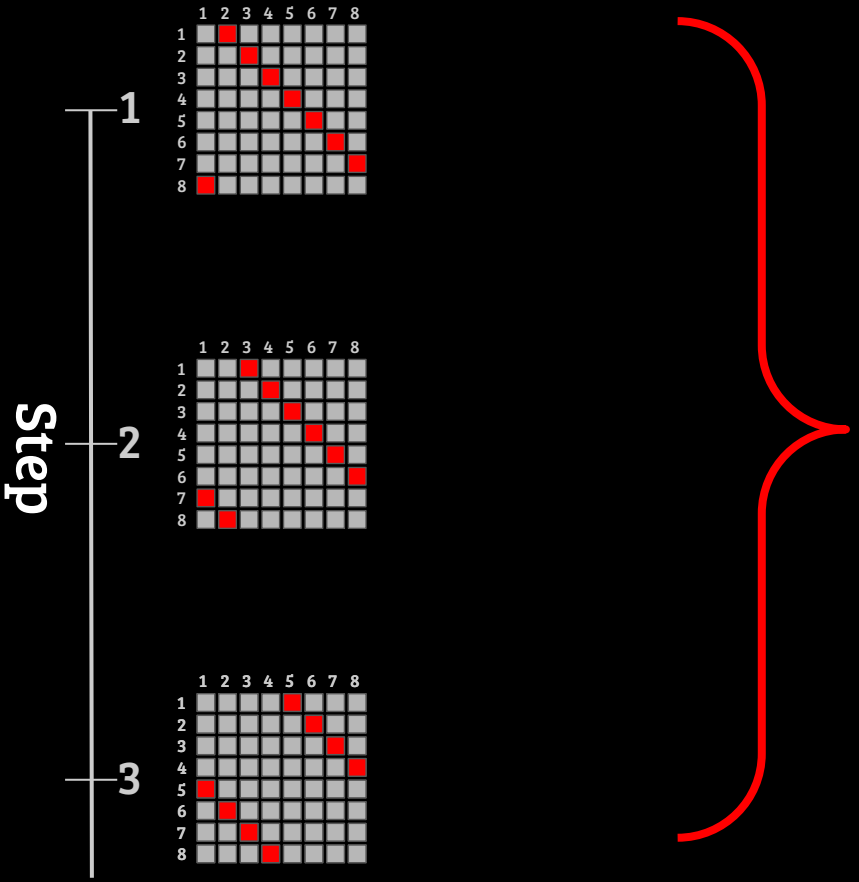
HARVEST

Example: Recursive Doubling (d = 2)

Unidirectional physical link

Communication

Demand Matrix



Example: Recursive Doubling (d = 2)

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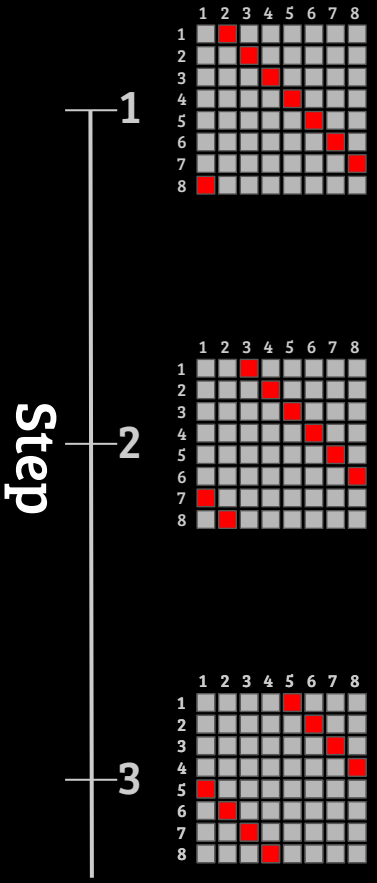
Communication

Demand Matrix



What is the optimal topology?

Example: Recursive Doubling (d = 2)

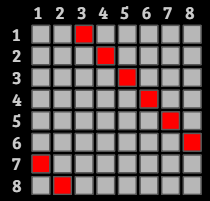
Unidirectional physical link

Communication

Demand Matrix

Step

1



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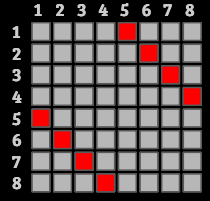


3

Direct-connect according to the first step

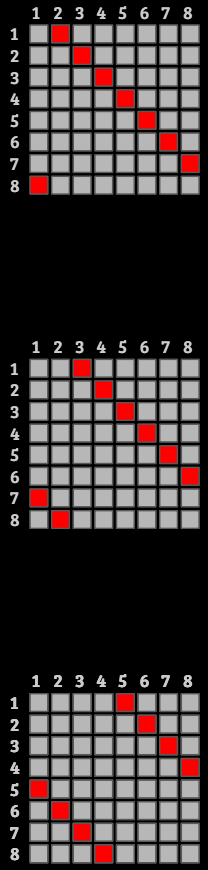
Maintains connectivity & optimal!

Example: Recursive Doubling (d = 2)

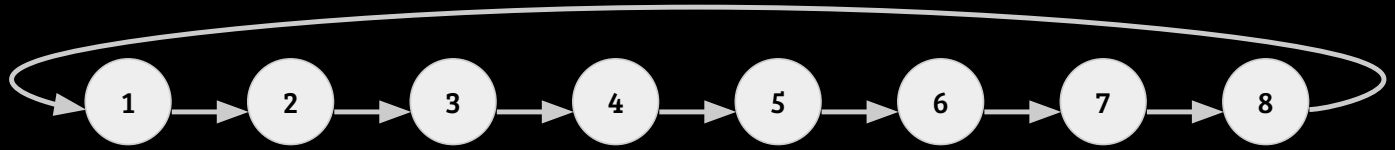
Unidirectional physical link

Communication

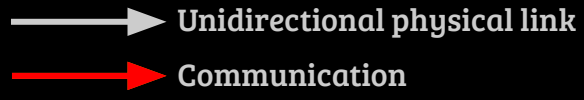
Demand Matrix



Topology



Example: Recursive Doubling (d = 2)



Demand Matrix

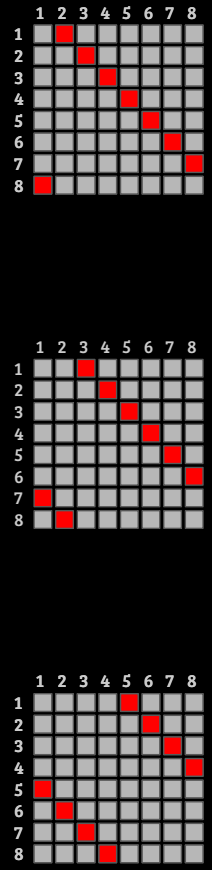
Topology

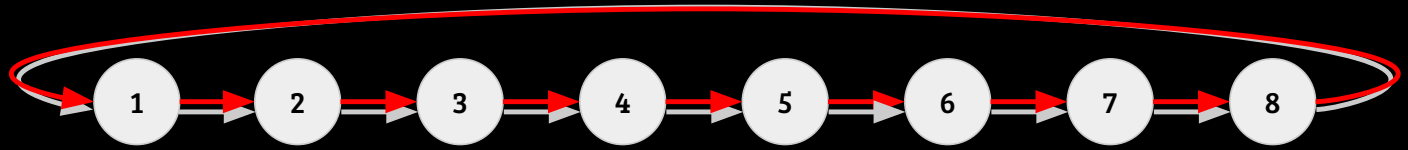
Step

1

2

3





Example: Recursive Doubling (d = 2)

Unidirectional physical link

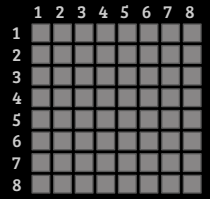
Communication

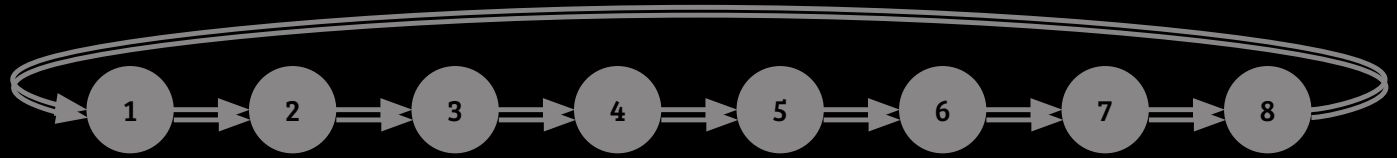
Demand Matrix

Topology

Step

1





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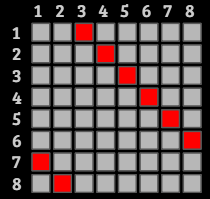

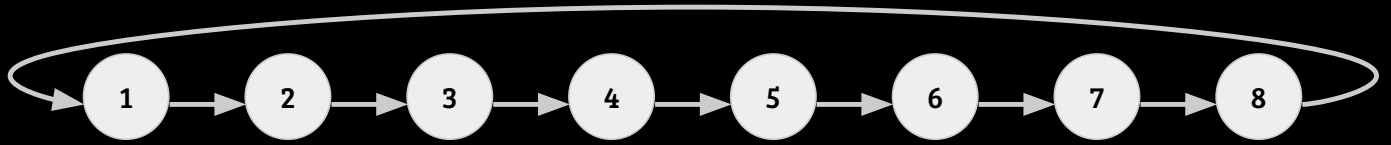

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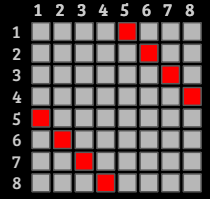


Example: Recursive Doubling (d = 2)

Unidirectional physical link

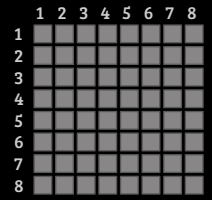
Communication

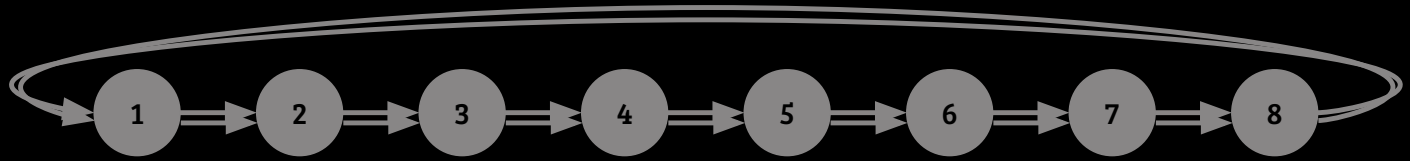
Demand Matrix

Topology

Step

1





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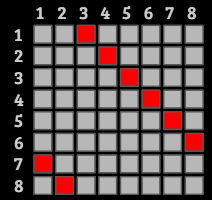

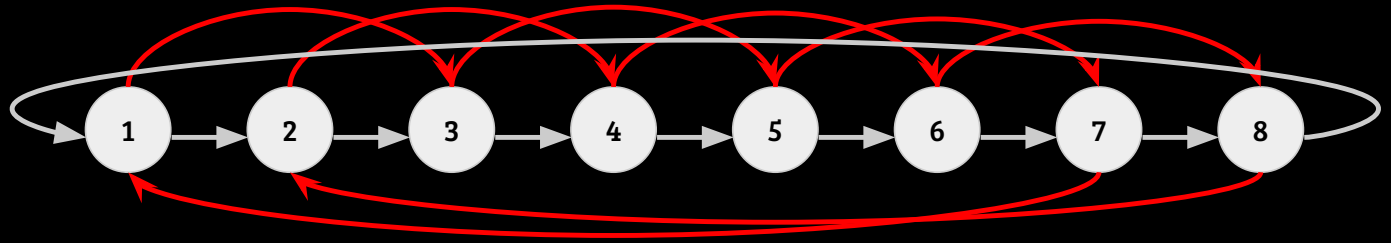

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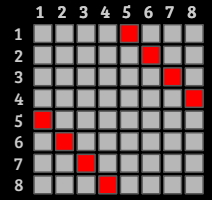


Example: Recursive Doubling (d = 2)

Unidirectional physical link

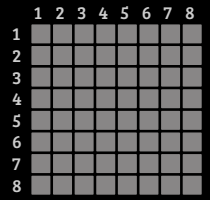
Communication

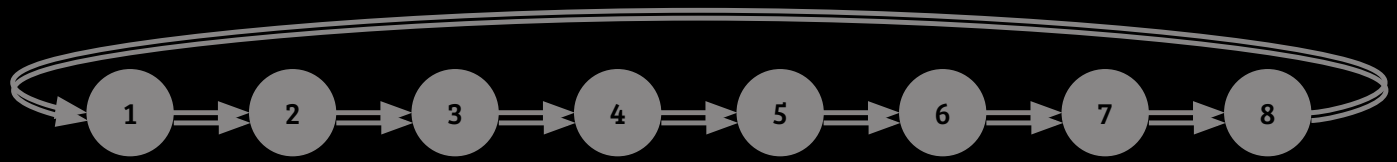
Demand Matrix

Topology

Step

1





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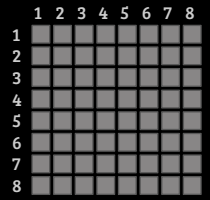

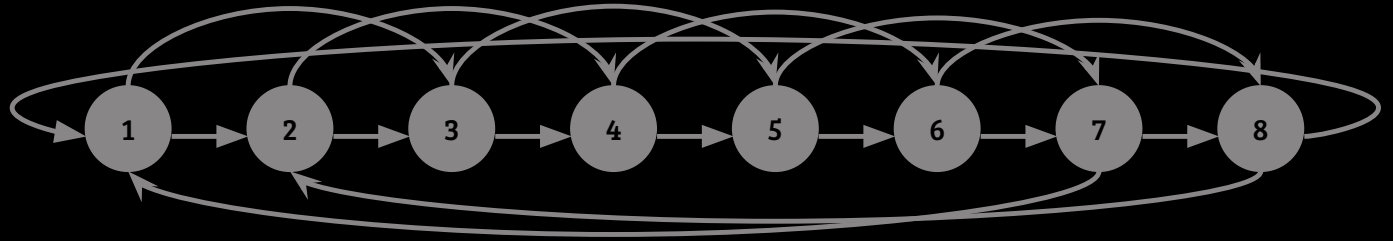

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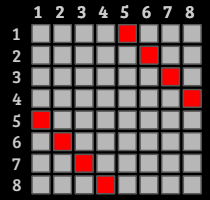
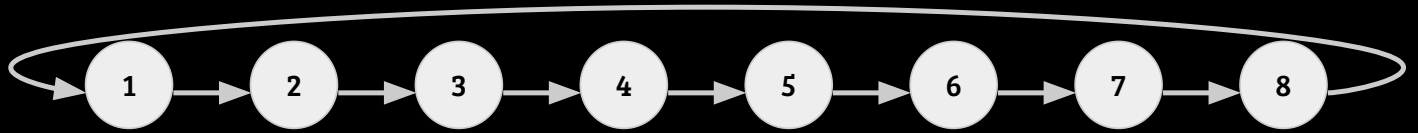
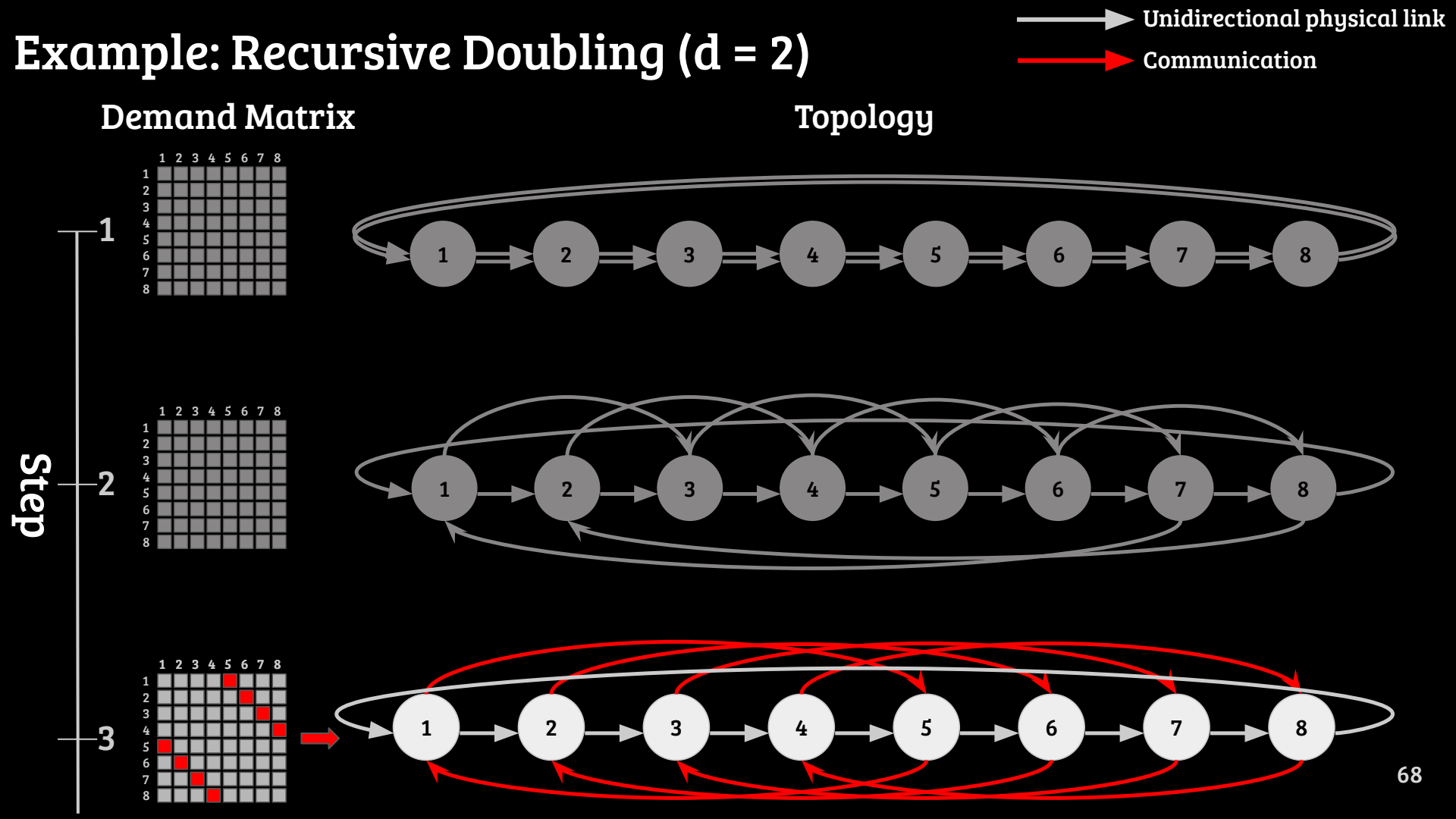




Example: Recursive Doubling (d = 2)



Example: Recursive Doubling (d = 2)

Unidirectional physical link

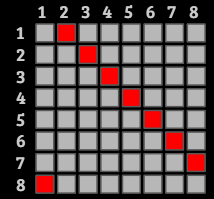
Communication

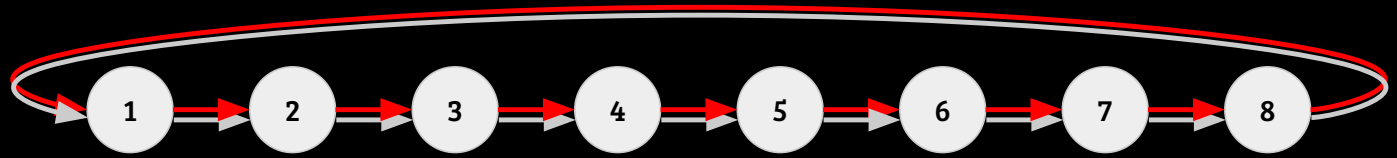
Demand Matrix

Topology

Step

1





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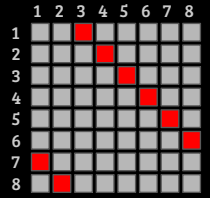

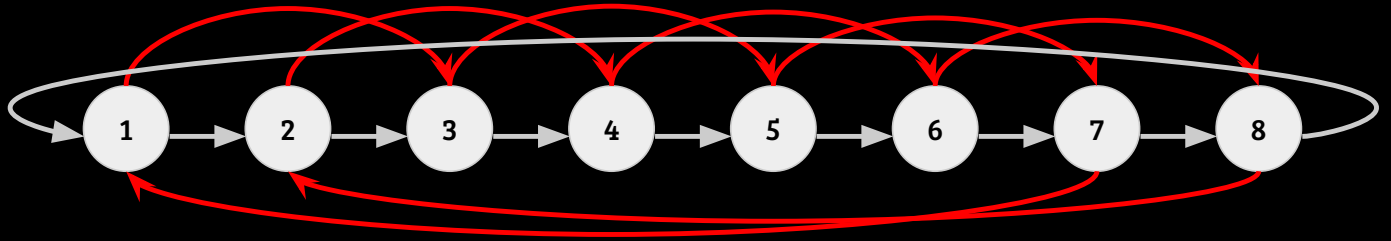

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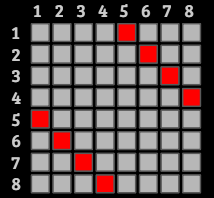

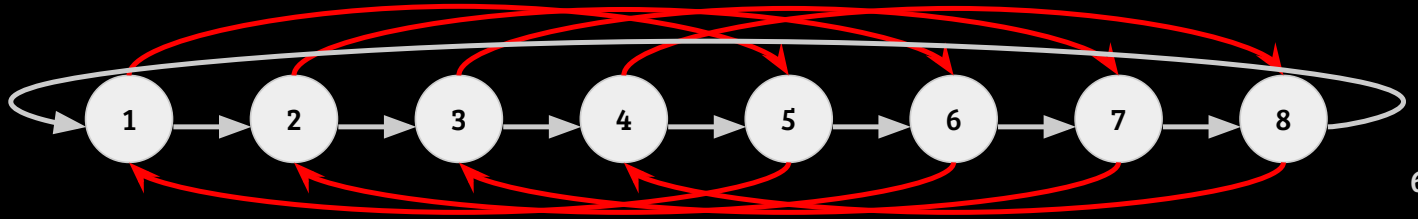

Example: Recursive Doubling (d = 2)

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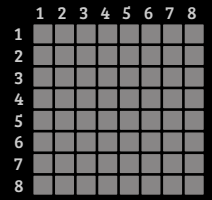
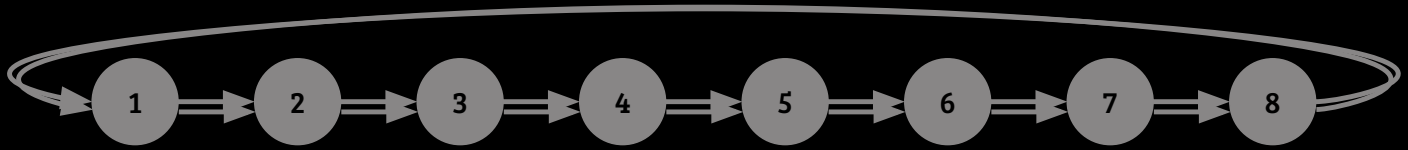


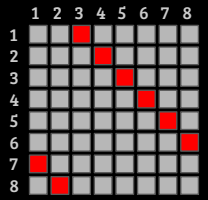


Reconfiguration event

Step

1

2



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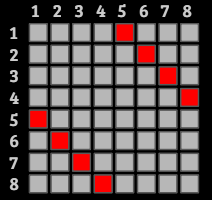


What is the optimal topology?

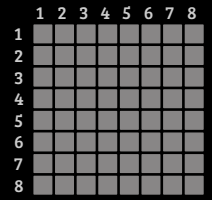
Example: Recursive Doubling (d = 2)

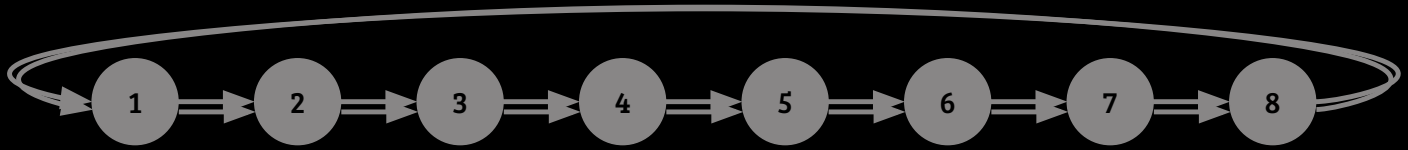
Unidirectional physical link

Communication

Demand Matrix

Topology





Reconfiguration event

Step

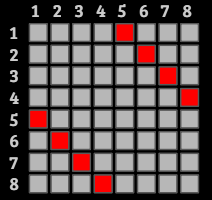
1

2

3

Direct-connect according to the first step

Maintains connectivity & optimal!



Example: Recursive Doubling (d = 2)

Unidirectional physical link

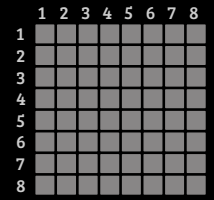
Communication

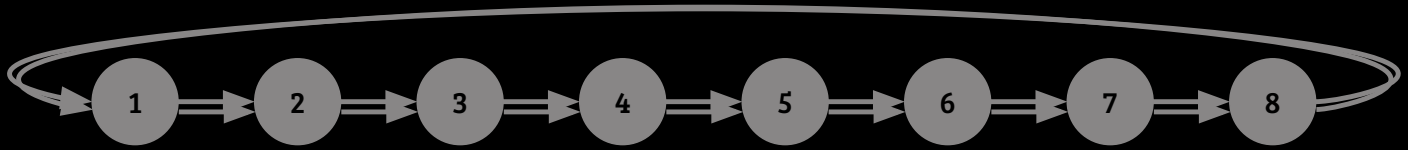
Demand Matrix

Topology

Step

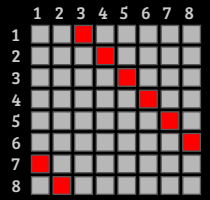
1

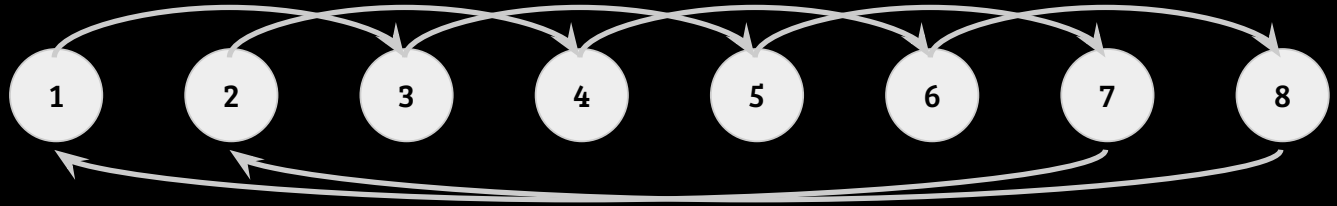




Reconfiguration event

2





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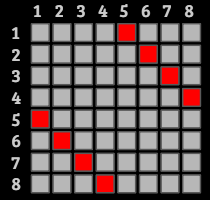


Example: Recursive Doubling (d = 2)

Unidirectional physical link

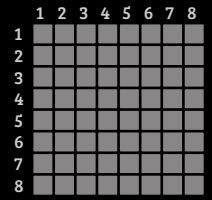
Communication

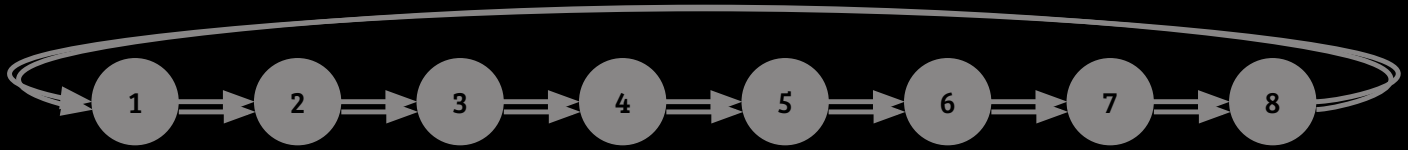
Demand Matrix

Topology

Step

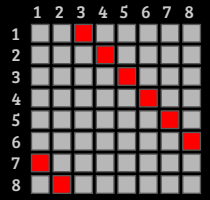
1

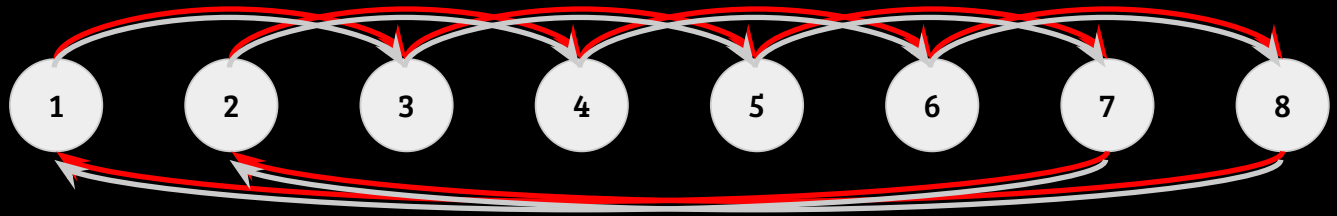




Reconfiguration event

2





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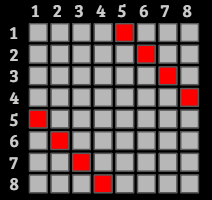


Example: Recursive Doubling (d = 2)

Unidirectional physical link

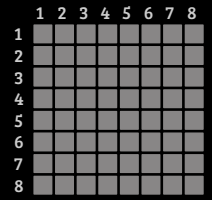
Communication

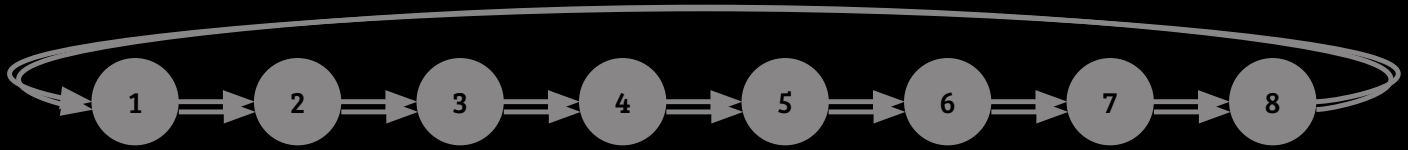
Demand Matrix

Topology

Step

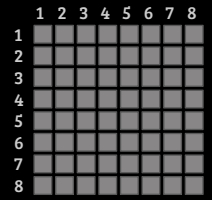
1

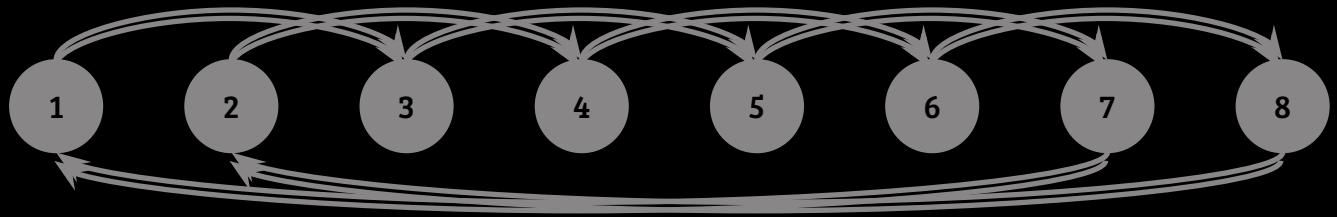




Reconfiguration event

2





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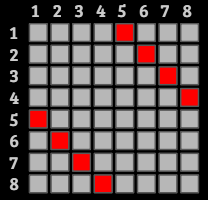

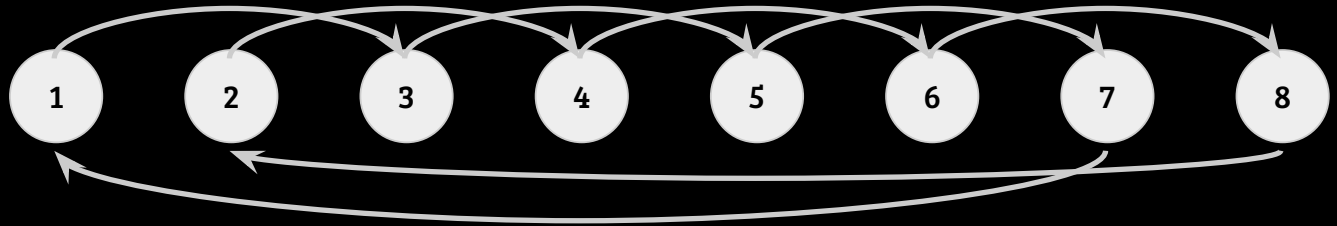

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Unidirectional physical link

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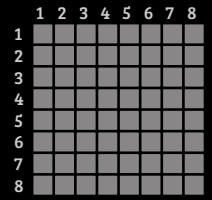
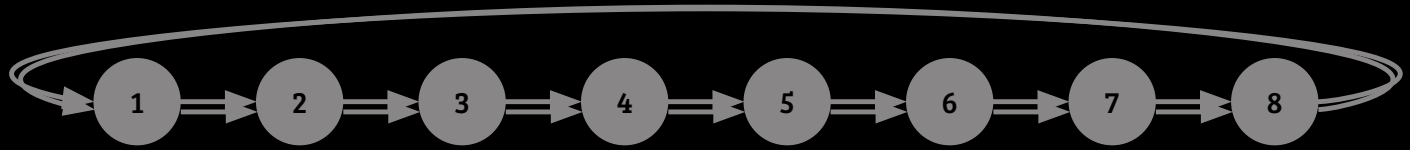
Topology

Step

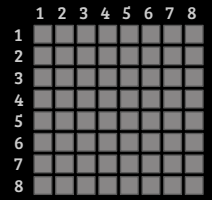
1

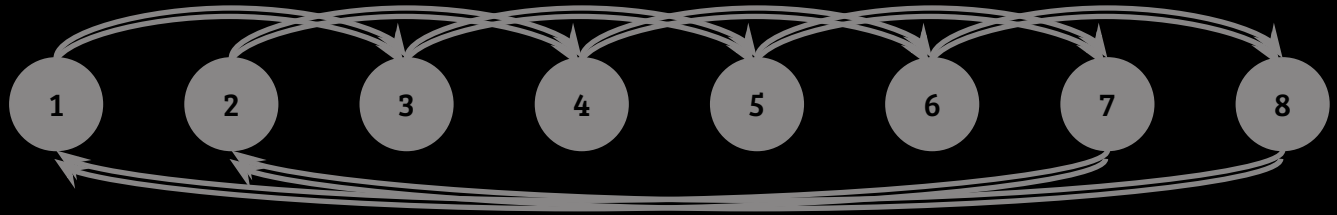




Reconfiguration event

2





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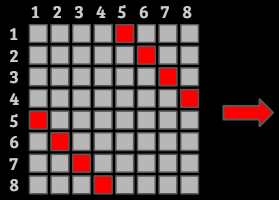
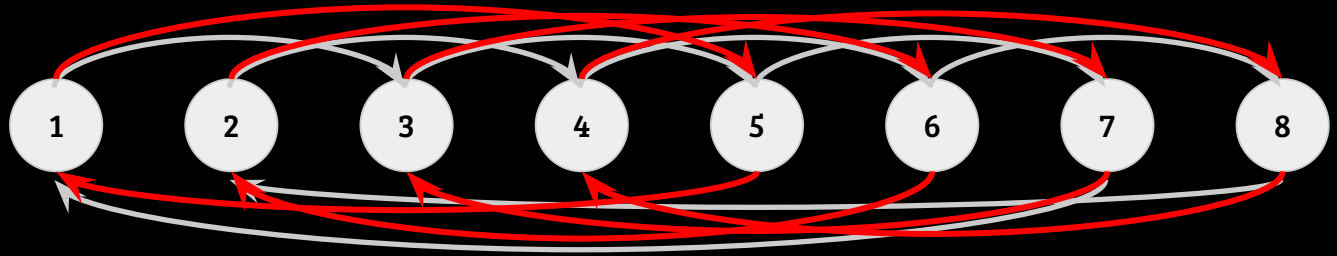




Example: Recursive Doubling (d = 2)

Unidirectional physical link

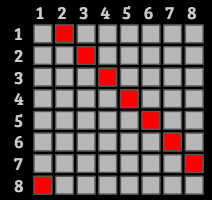
Communication

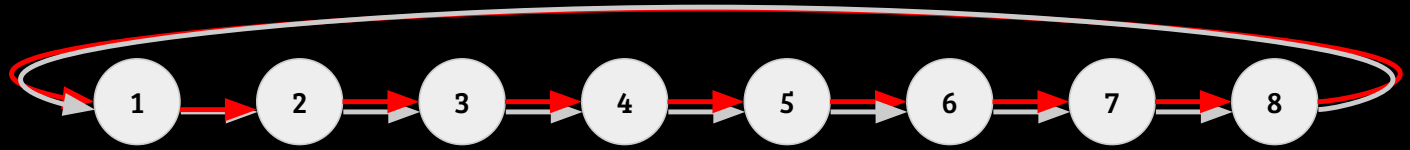
Demand Matrix

Topology

Step

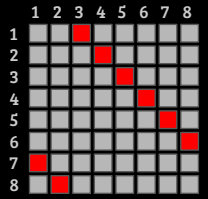
1

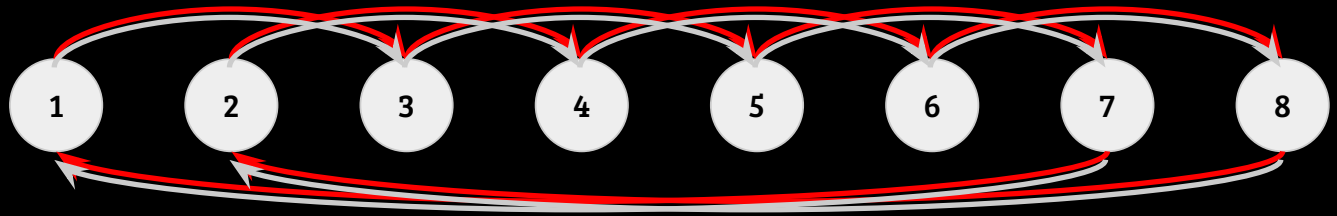




Reconfiguration event

2





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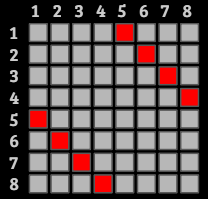

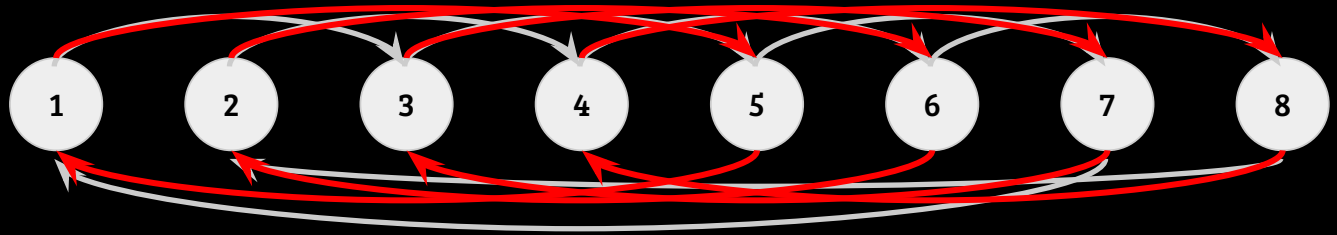

When and How to Reconfigure?

- Collectives with geometric distance progression
  node *i* communicates with node $i + d^k$ in step *k*
  - Recursive doubling: d = 2
  - Bruck's All-to-All and AllReduce: d = 3, 4, …, r
  - Hypercube All-to-All: d = 2
  - Trivance: d = 3

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When and How to Reconfigure?

1. ~~When? Partition the sequence of communication steps into intervals~~
   a. Dynamic programming ✅
2. ~~How? Find an optimal static topology for each interval~~
   a. MISOCP ✅ (For generality)
   b. Direct-connect ✅ (For collectives with geometric distance progression)

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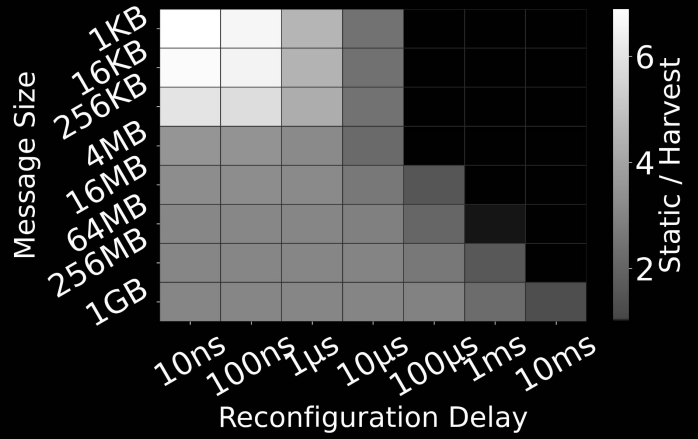
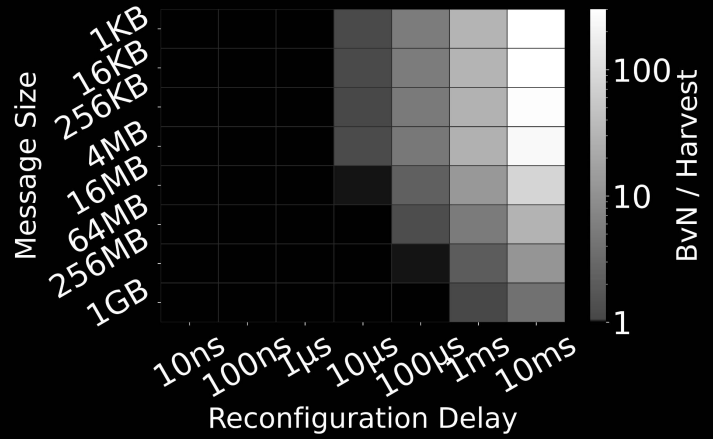
Evaluation Methodology

- We compare performance of Harvest against two baselines:
  - A static topology
  - Schedules that reconfigure every step (BvN)
- Network sizes: 8 to 64 GPUs
- Reconfiguration delays: 10 ns to 10 ms
- Message sizes: 1 KB to 1 GB

Speed-Up for Recursive Doubling AllReduce

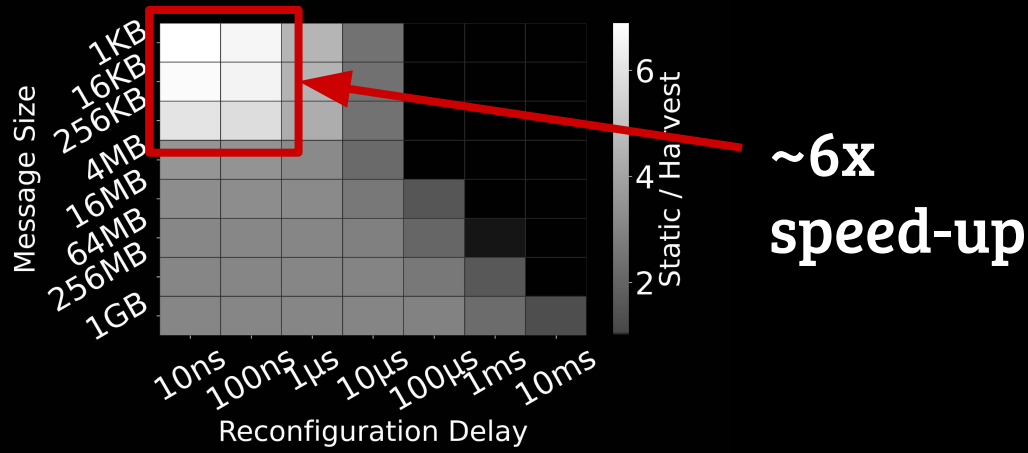
- Baseline/Harvest Ratio > 1 –> Harvest outperforms
- Baseline/Harvest Ratio == 1 –> Harvest matches performance





Speed-Up for Recursive Doubling AllReduce

- Static vs Harvest
- Low message size and low reconfiguration delay domains show more than 6x speed-up over Static



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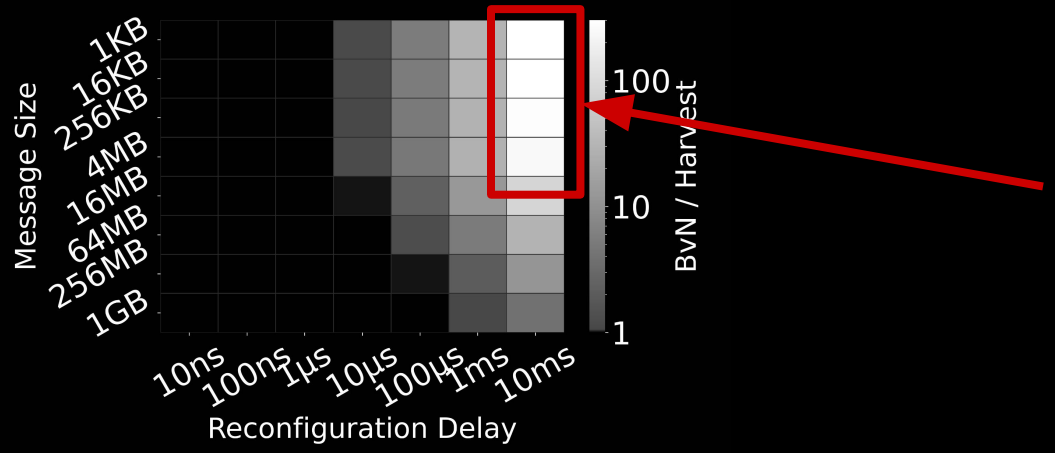
Speed-Up for Recursive Doubling AllReduce

- Reconfigure every step schedule (BvN) vs Harvest
- Low message size and high reconfiguration delay domains show significant speed-up over BvN



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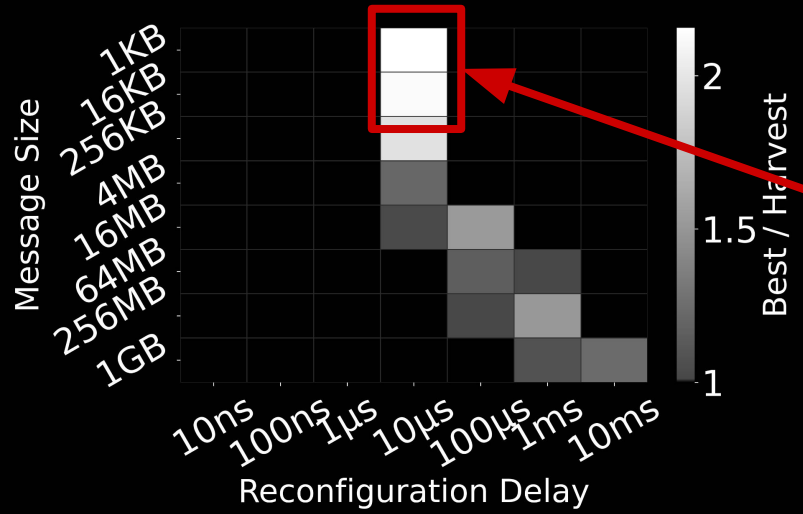
Speed-Up for Recursive Doubling AllReduce

- Harvest vs Best of (Static, BvN)
- A new space where Harvest outperforms both



~2x speed-up

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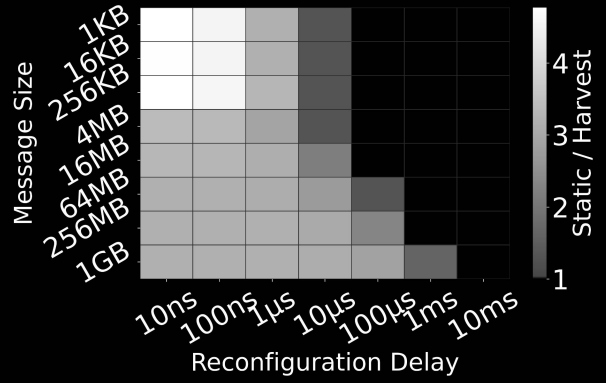
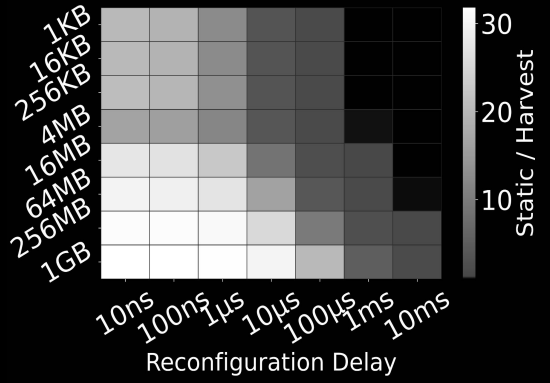
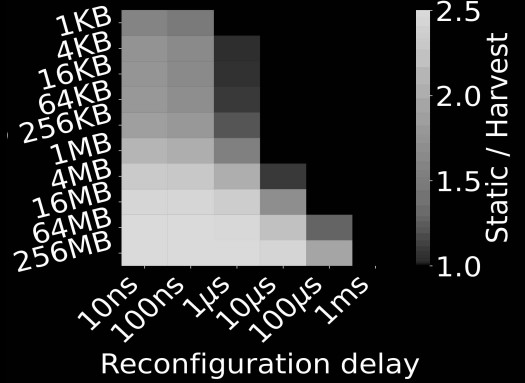
Performance comparison to other collectives



Swing



Cyclic All-to-All



Bruck r = 4 AllGather

And many more…

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Conclusion

- There is a need to balance network congestion and reconfiguration delay to minimize collective completion time
- We present an optimization framework to synthesize optimal topologies
- O(1) reduction in topology search space for most well-known algorithms

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Thank You

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