Disaggregating Persistent Memory and Controlling Them Remotely: An Exploration of Passive Disaggregated Key-Value Stores

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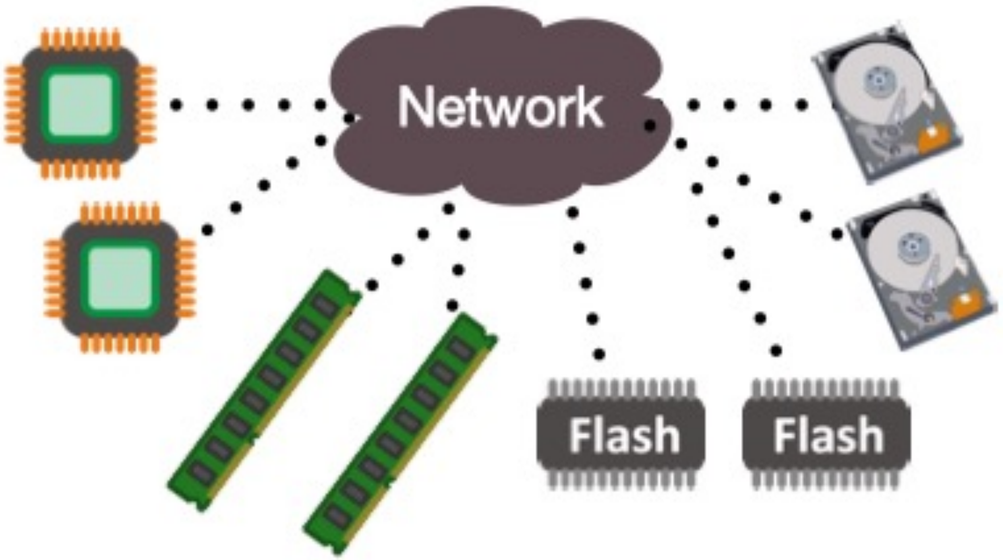
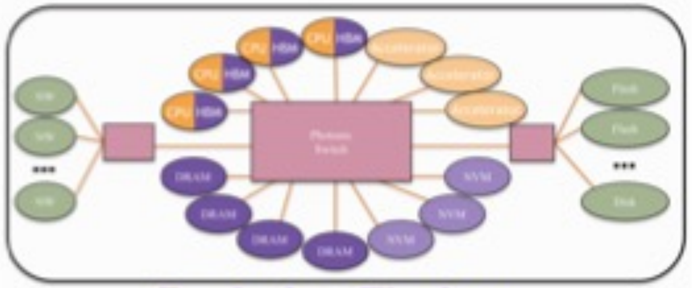
Resource Disaggregation

Break monolithic servers into ***network-attached*** resource pools

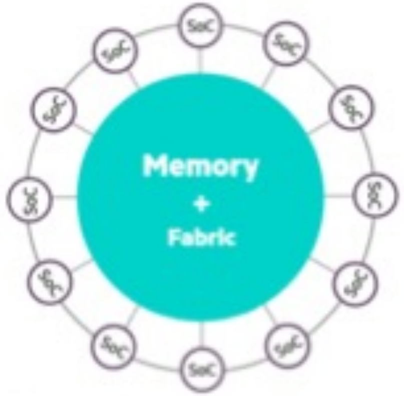
Better manageability, independent scaling, tight resource packing



LegoOS



Berkeley Firebox



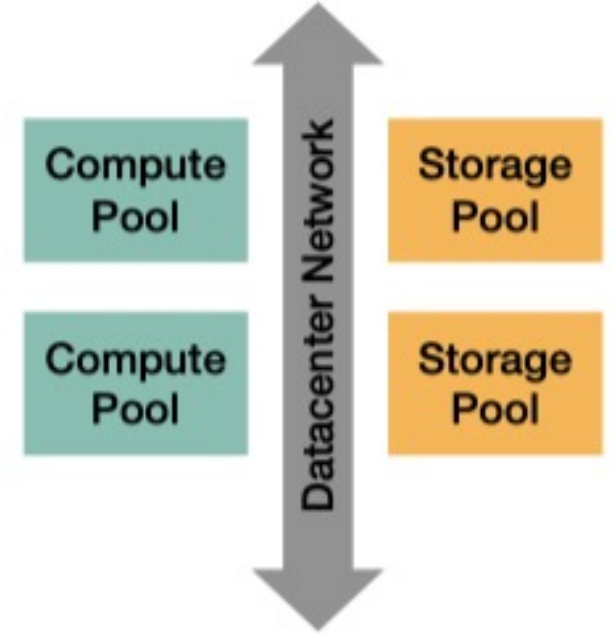
Hewlett Packard Enterprise

Disaggregated Storage

Separate compute and storage pools

- Manage and scale independently

A common practice in datacenters and clouds



amazon web services | S3

facebook Engineering

Powered By vmware vSAN

snowflake

Alibaba Singles' Day 2019 had a Record Peak Order Rate of 544,000 per Second

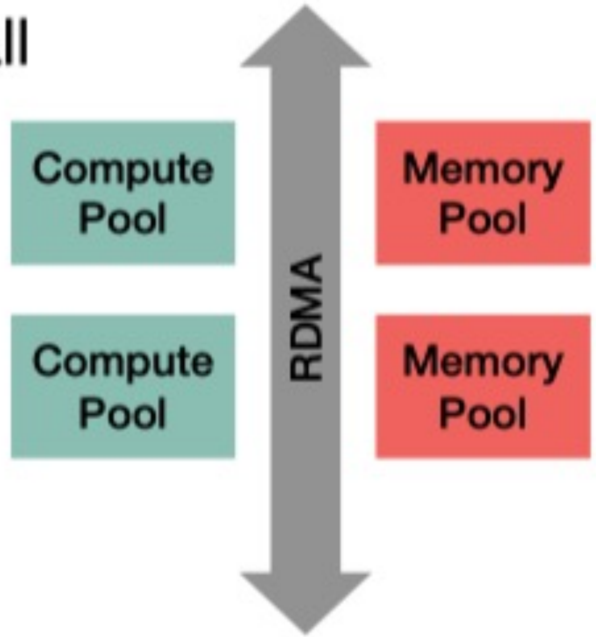
Yash Wate

Disaggregated Memory

- Network is getting faster (e.g., 200 Gbps, sub-600 ns)
- Application need for large memory + memory-capacity wall

➡ Remote/disaggregated memory

  - Applications access (large) non-local memory

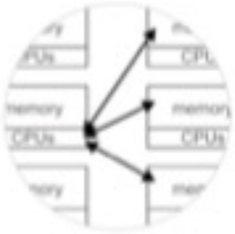


Microsoft

FaRM

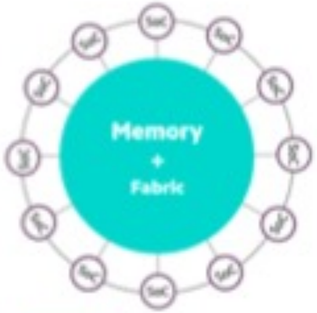
vmware

Remote memory



HUAWEI

HTC-DC



Hewlett Packard Enterprise

Memory Blades, ISCA'09
NAM-DB, VLDB'17
ZombieLand, EuroSys'18
StRoM, EuroSys'20

Disaggregated Persistent Memory?

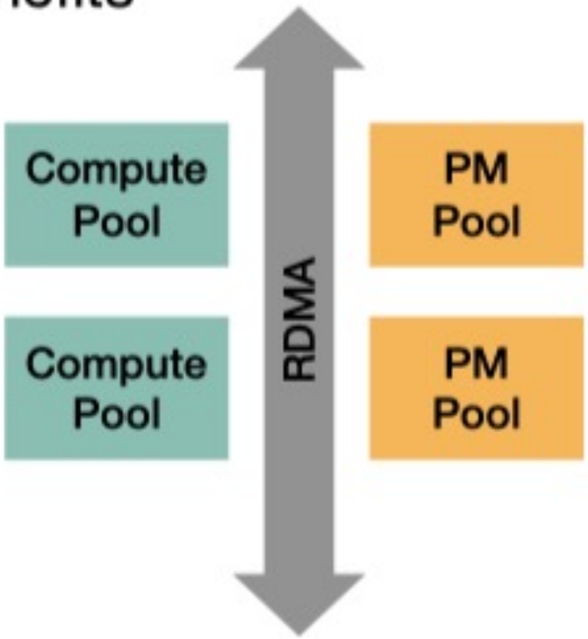
PM: byte-addressable, persistent, memory-like perf

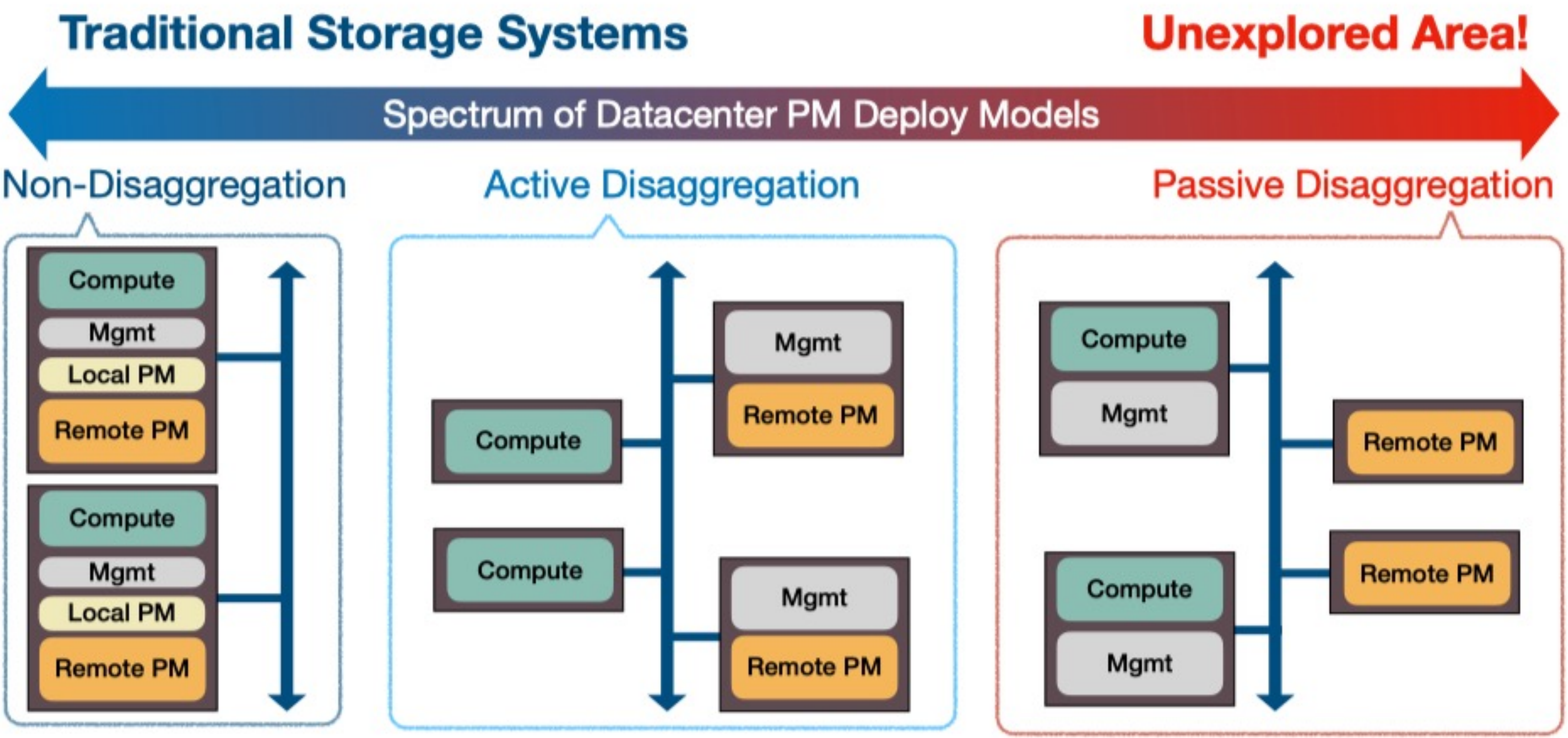
Disaggregating PM (DPM)

- Enjoy disaggregation's management, scalability, utilization benefits
- Easy way to integrate PM into current datacenters

Use existing disaggregated systems for DPM?

- Disaggregated storage: software stack too slow for fast PM
- Disaggregated memory: do not provide data reliability




Traditional Storage Systems
Unexplored Area!
Spectrum of Datacenter PM Deploy Models
Non-Disaggregation
Active Disaggregation
Passive Disaggregation
Compute
Mgmt
Local PM
Remote PM
Compute
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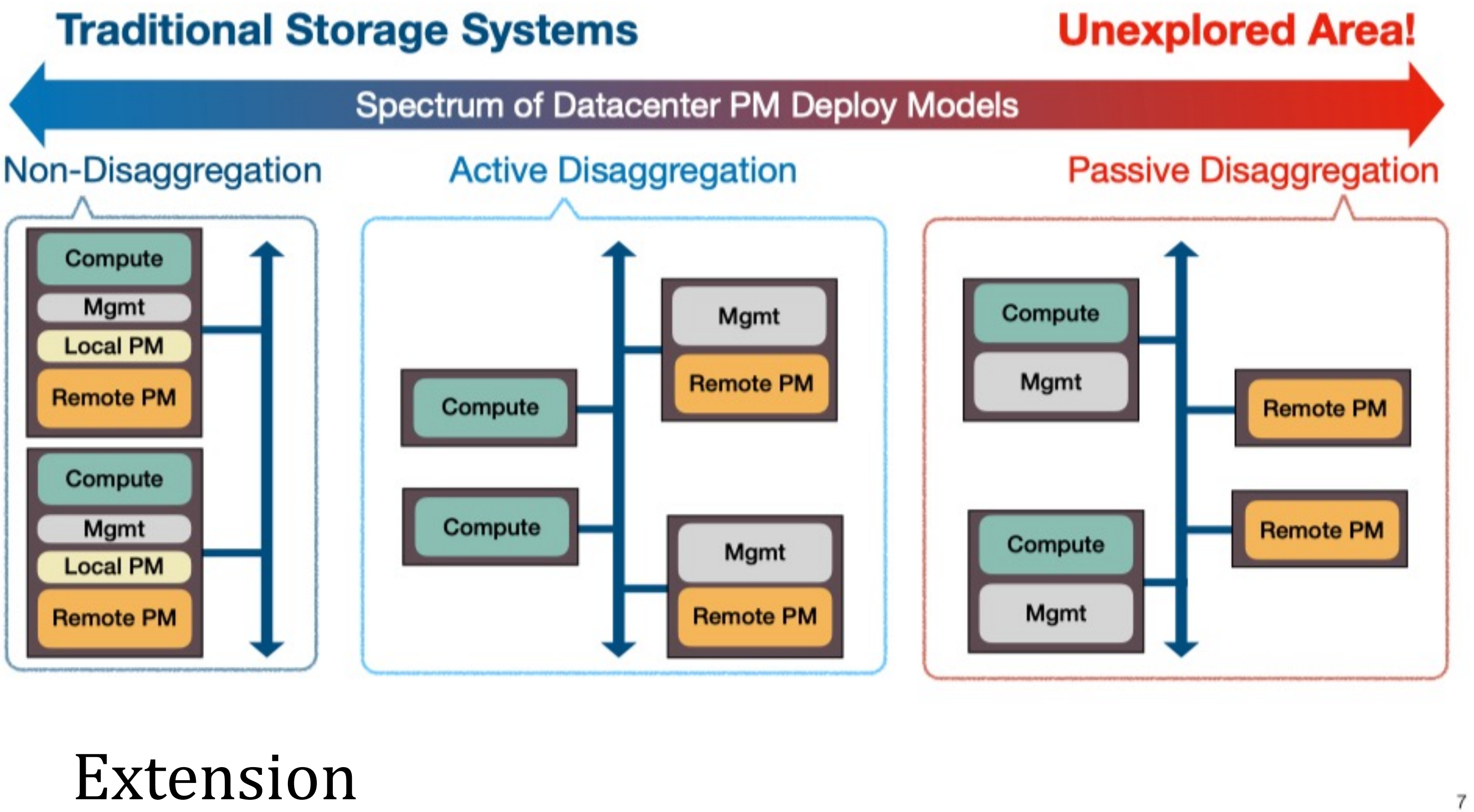
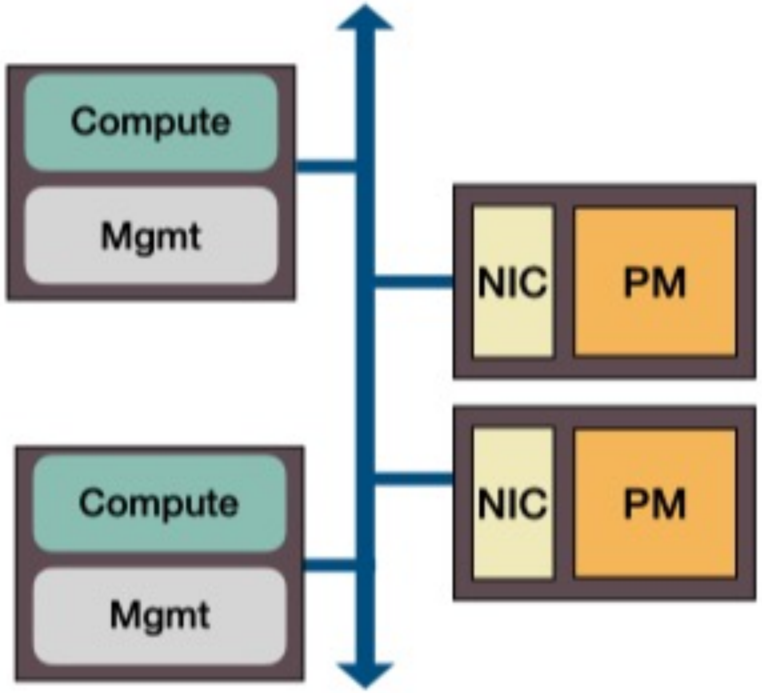


Extension

- What is **Mgmt**?
- Difference between **Active** Disaggregation and **Passive** Disaggregation ?
  - One-sided RDMA and Two-sided RDMA
  - Passive’s target is eliminating polling in DN CPU.

Passive Disaggregated PM (pDPM)



pDPM

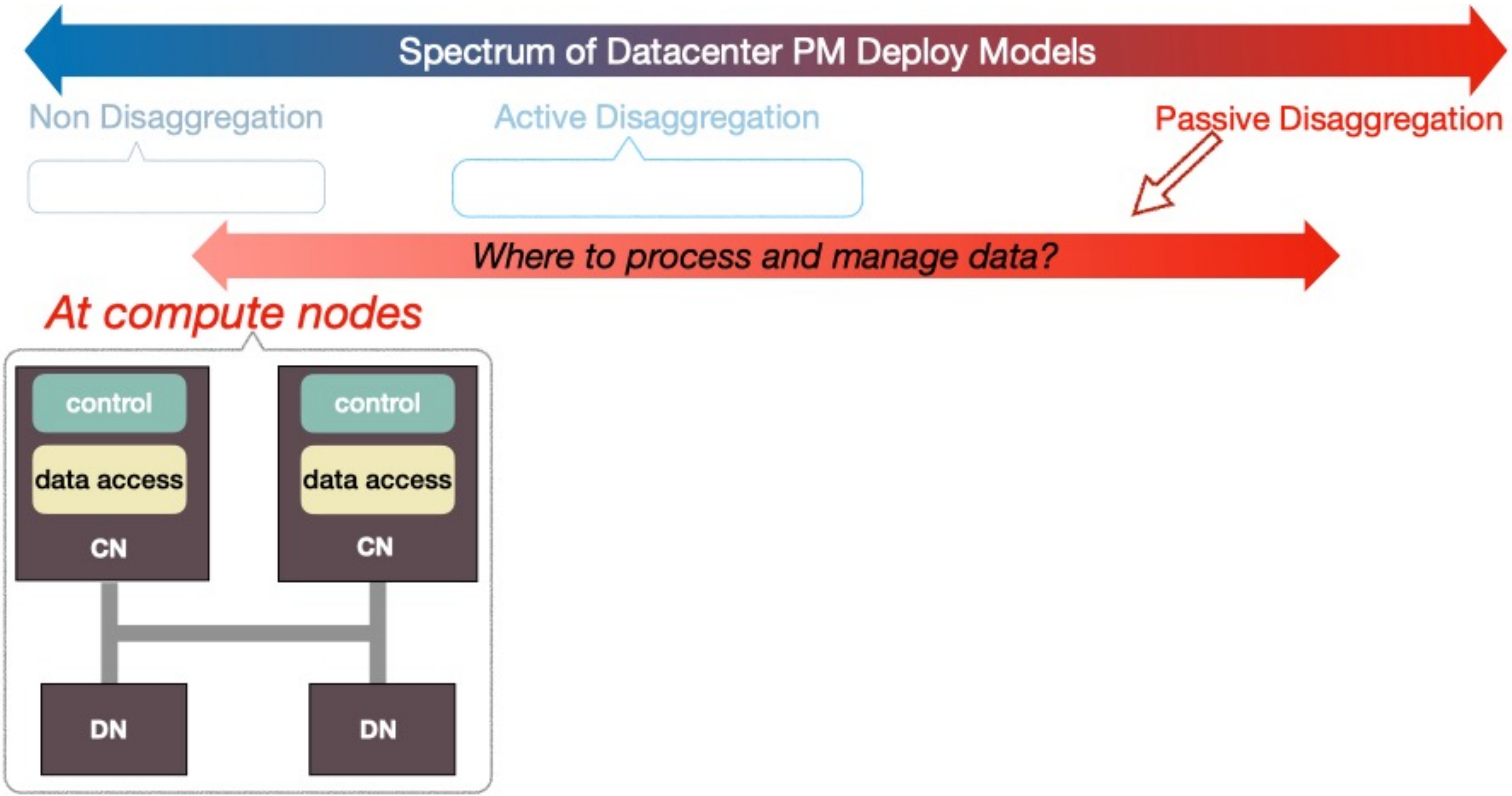
- Passive PM devices with NIC and PM
- Accessible only via network

Why pDPM?

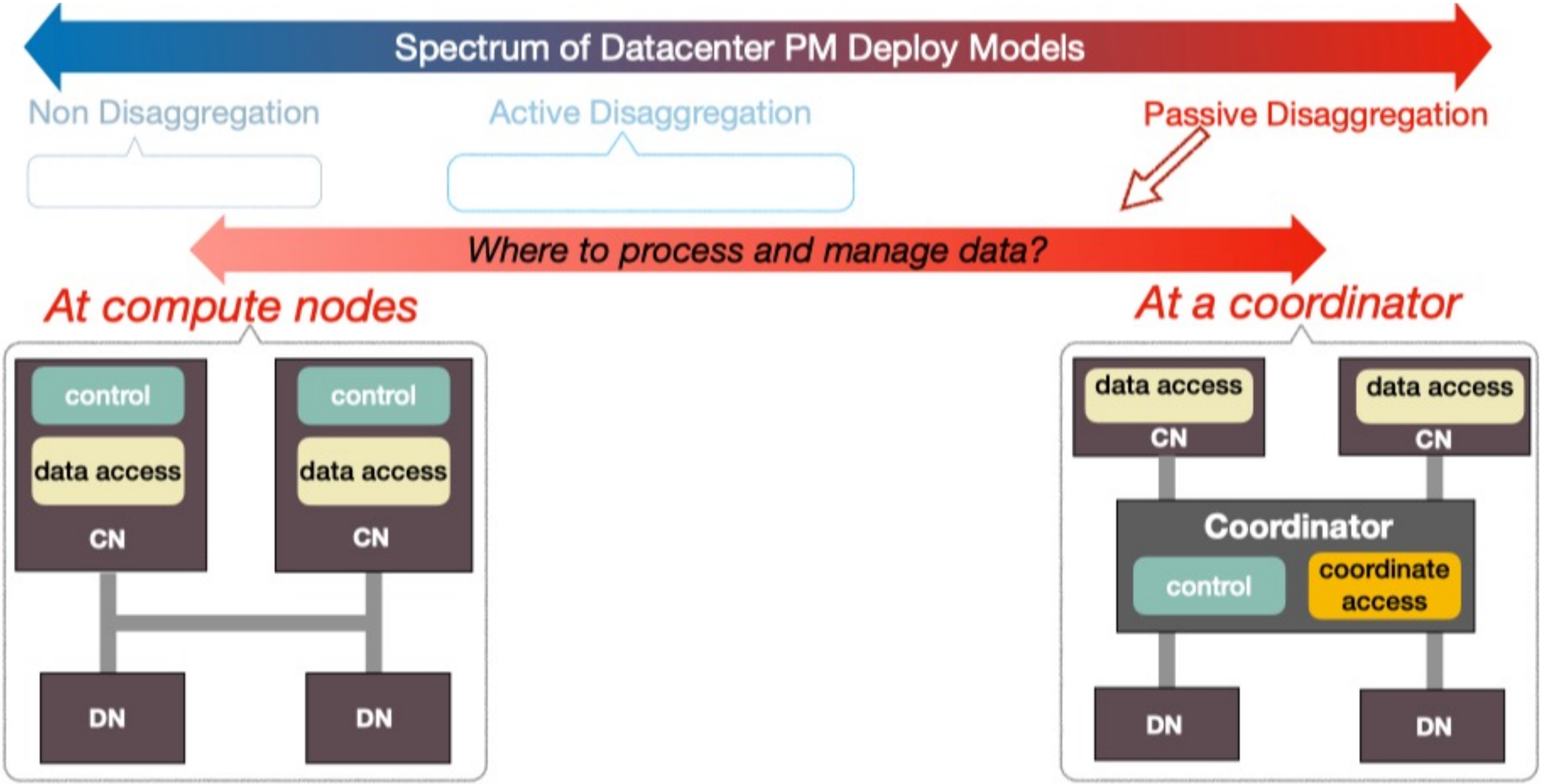
- Low CapEx and OpEx
- Easy to add, remove, and change
- No scalability bottleneck at storage nodes
- Research value in exploring new design area

Why possible now? Fast RDMA network + CPU bypassing

Without processing power at PM, where to process and manage data?



CN: Compute Node, **DN**: Data Node with PM



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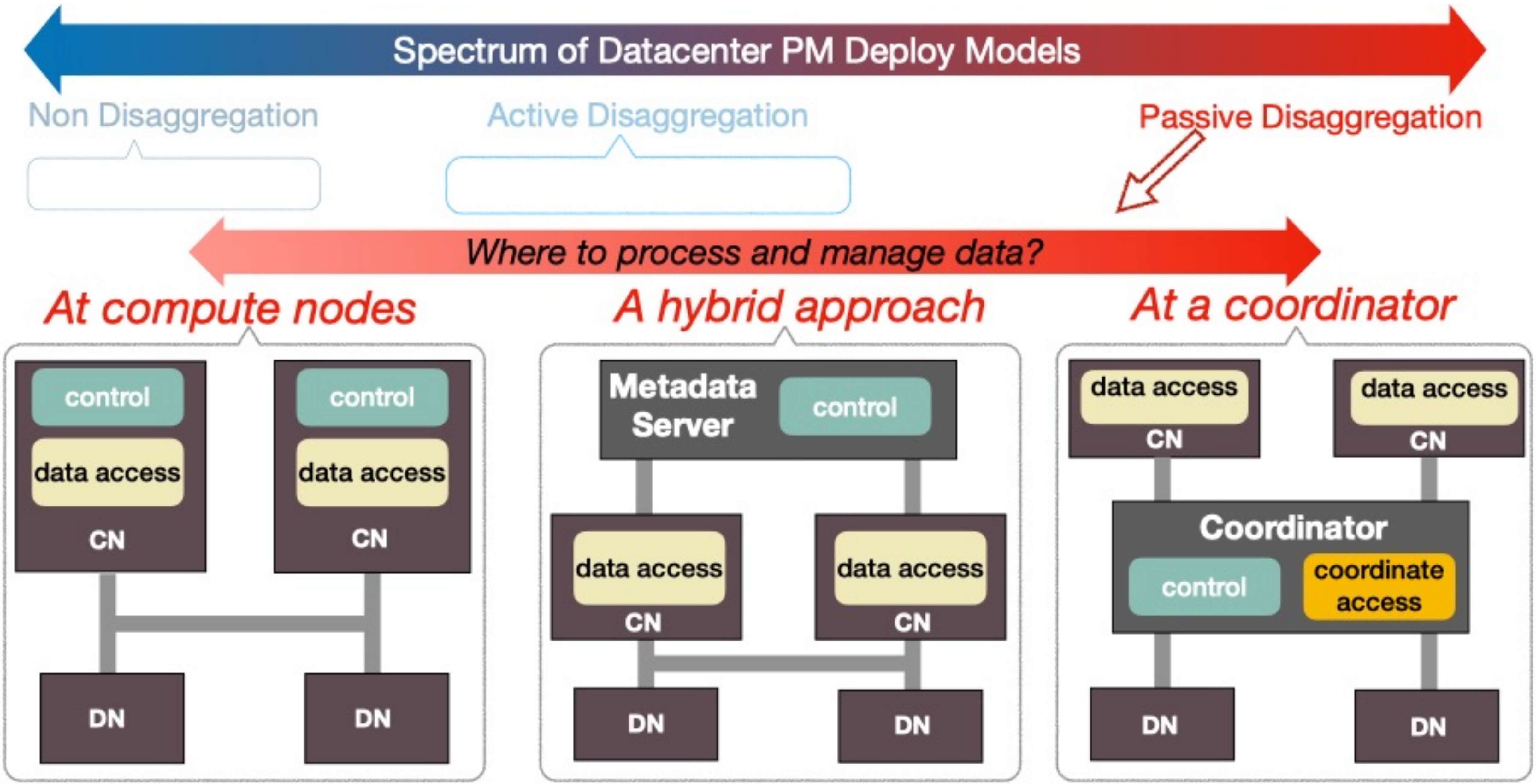
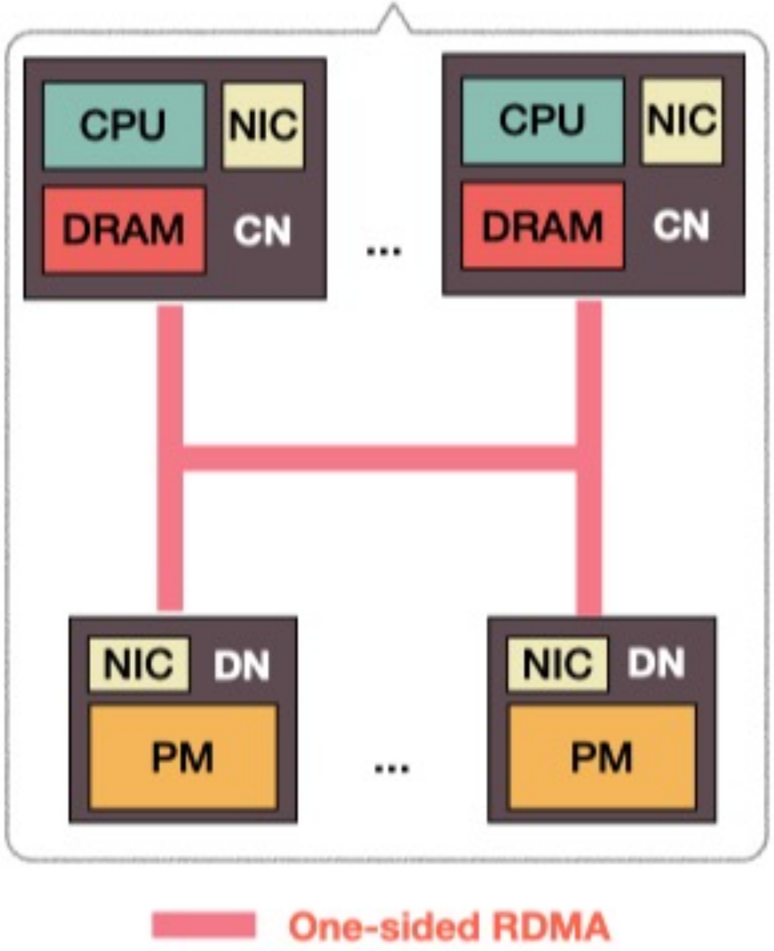


CN: Compute Node, **DN**: Data Node with PM

Passive Disaggregated PM (pDPM) Systems

- We design and implement three pDPM key-value stores
  - At computer nodes → **pDPM-Direct**
  - At global coordinator → **pDPM-Central**
  - A hybrid approach → **Clover**
- Carry out extensive experiments: performance, scalability, costs
- Clover is the best pDPM model: perf similar to active DPM, but lower costs
- Discovered tradeoffs between passive and active DPMs

pDPM-Direct: Directly Access and Manage DNs from CNs



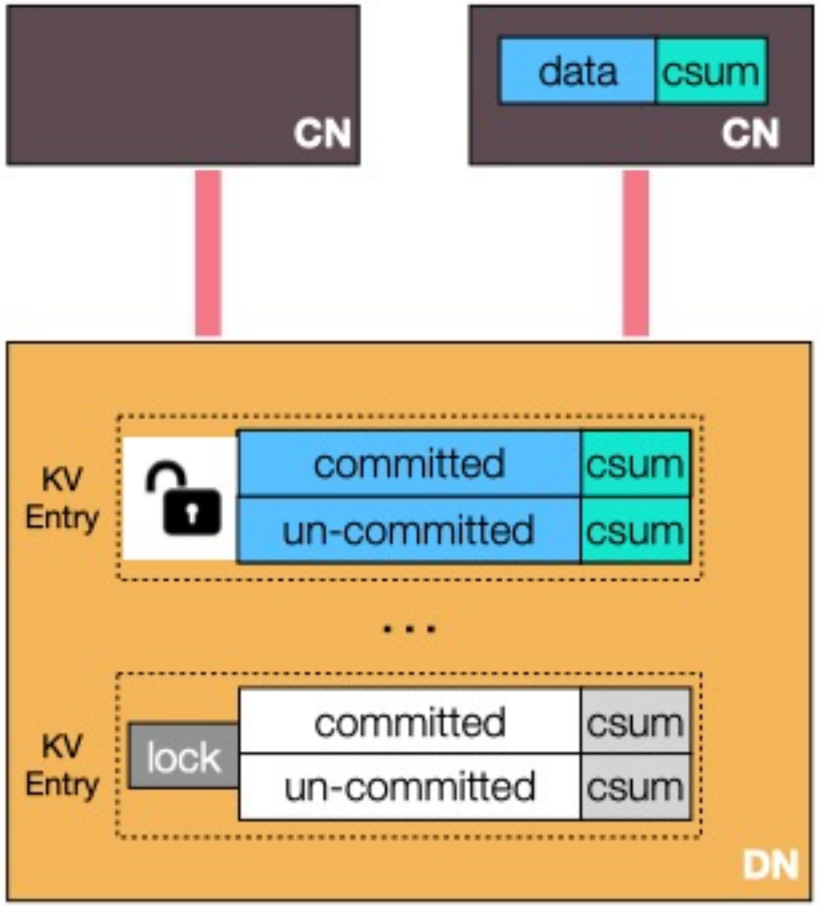
Overall Architecture

- CNs access and manage DNs directly via one-sided RDMA
- Both data and control planes run within CNs

Challenges

- How to manage DN space?
- How to coordinate concurrent reads/writes across CNs?

pDPM-Direct



Our solution

- Pre-assign two spaces for each KV entry (`committed+uncommitted`)
- Lock-free, checksum-based read (`csum`)
- RDMA c&s-based write lock (`lock`)

Write Flow

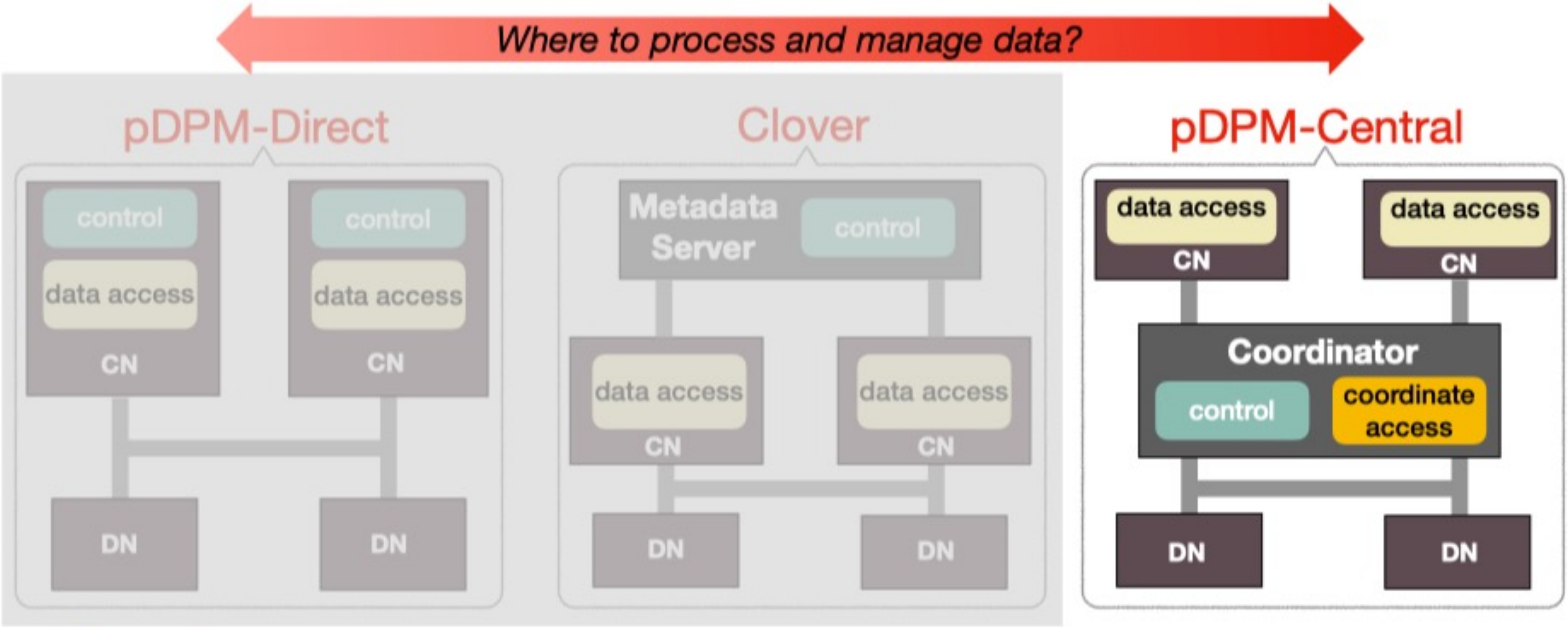
- Acquire lock
- Write new data+CRC into `uncommitted` space (redo-copy)
- Write new data+CRC into `committed` space
- Release lock

Read Flow

- CN reads committed data and CRC
- CN checks if CRC match. If mismatch, retry

Best case
Write: 4 RTT + csum calc
Read: 1 RTT + csum calc

Slow write
Slow with large data
Poor scalability under concurrent accesses



- Slow write
- Slow for large data

Distributed data & metadata planes

Centralized data & metadata planes

pDPM-Central: A Central Coordinator between CNs and DNs

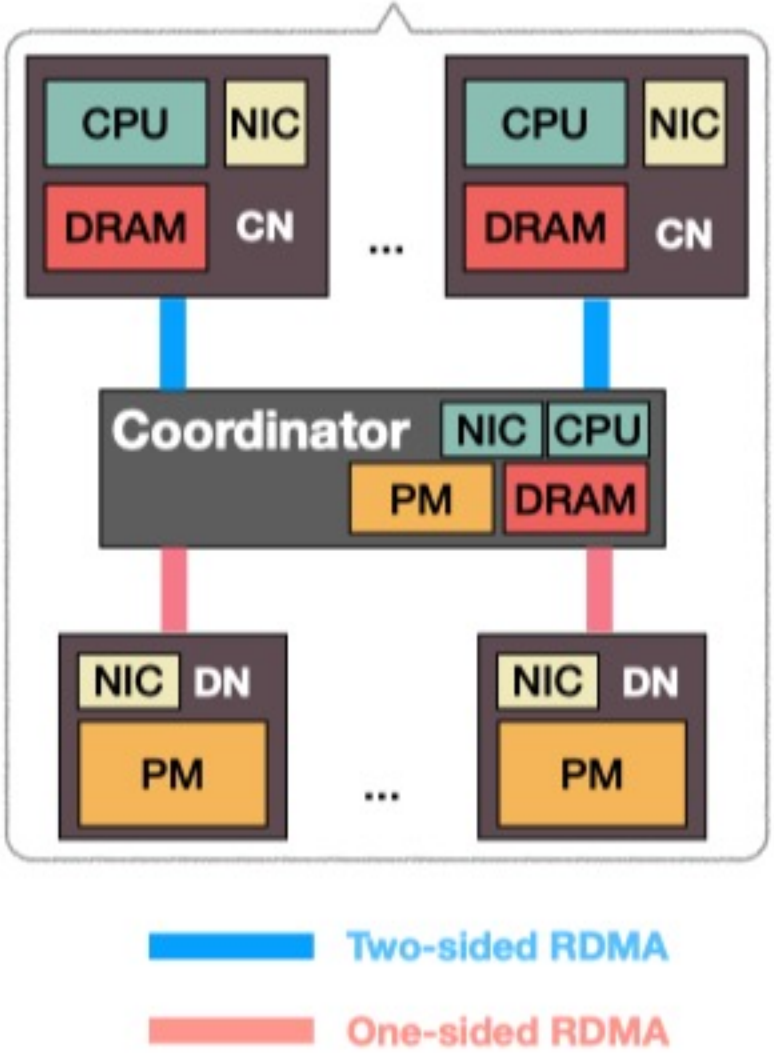
The central coordinator

- Manages DN space
- Serializes CNs accesses with local locking

CNs communicate with the coordinator through two-sided RDMA

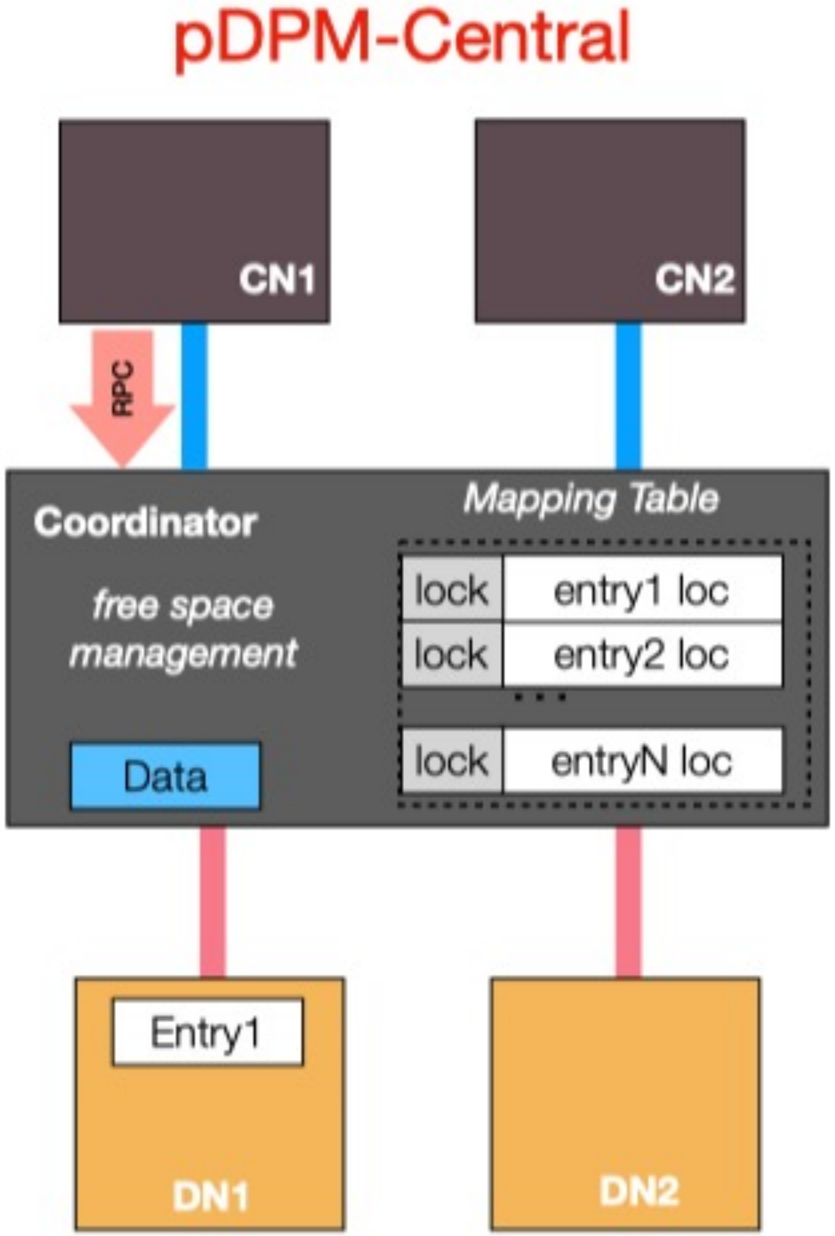
Coordinator accesses DNs through one-sided RDMA

☺ **Easier to manage DNs and coordinate concurrent accesses**



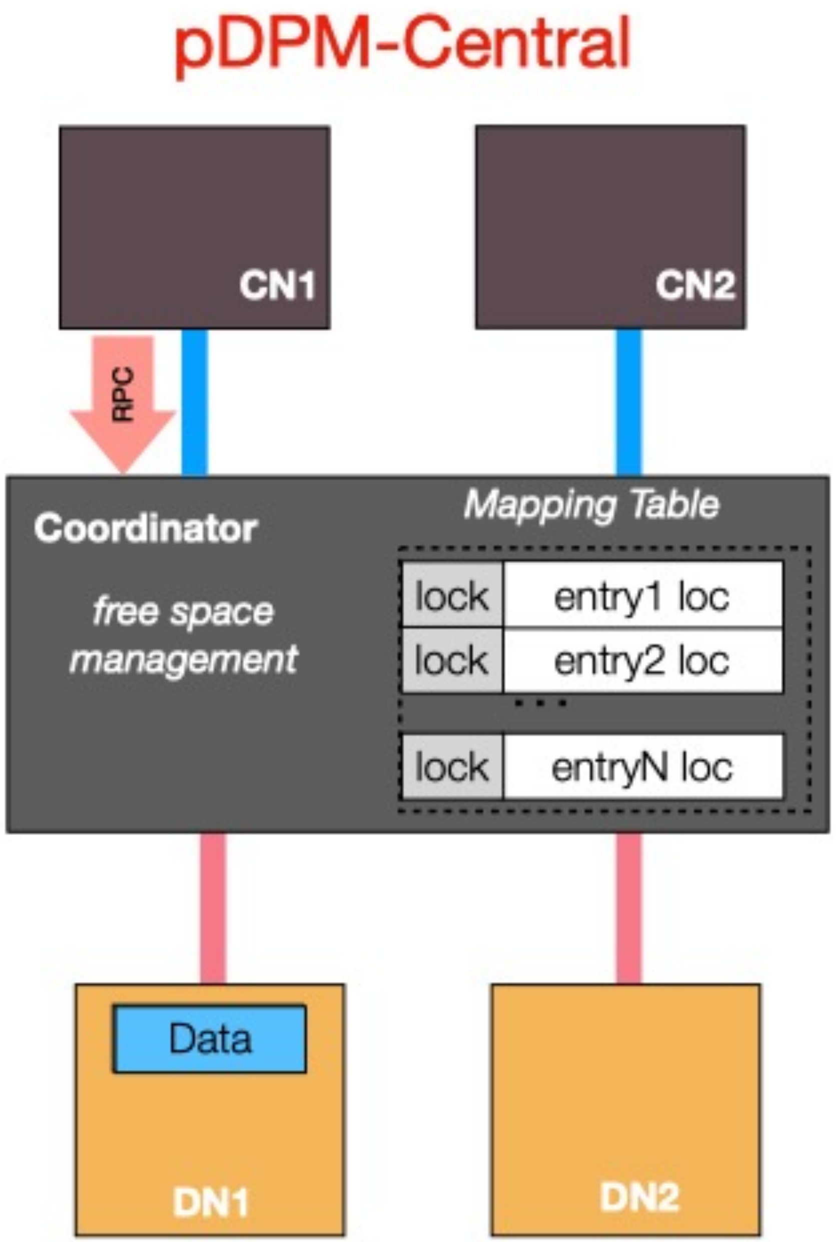
Write Flow

- CN sends RPC (with data) to Coordinator
- Coordinator allocates a new space for the write



Write Flow

- CN sends RPC (with data) to Coordinator
- Coordinator allocates a new space for the write
- Coordinator writes data to it (as redo-copy)



Write Flow

- CN sends RPC (with data) to Coordinator
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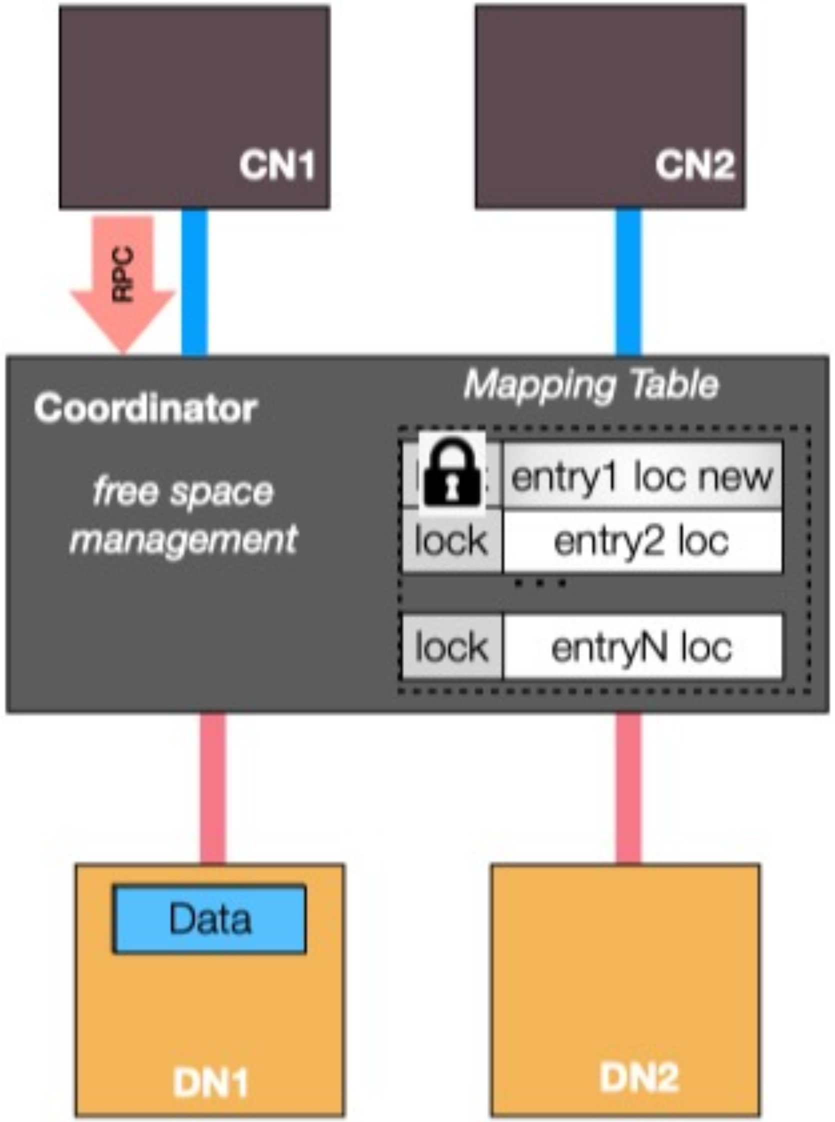
- Coordinator updates its local map table (with a local lock)

pDPM-Central



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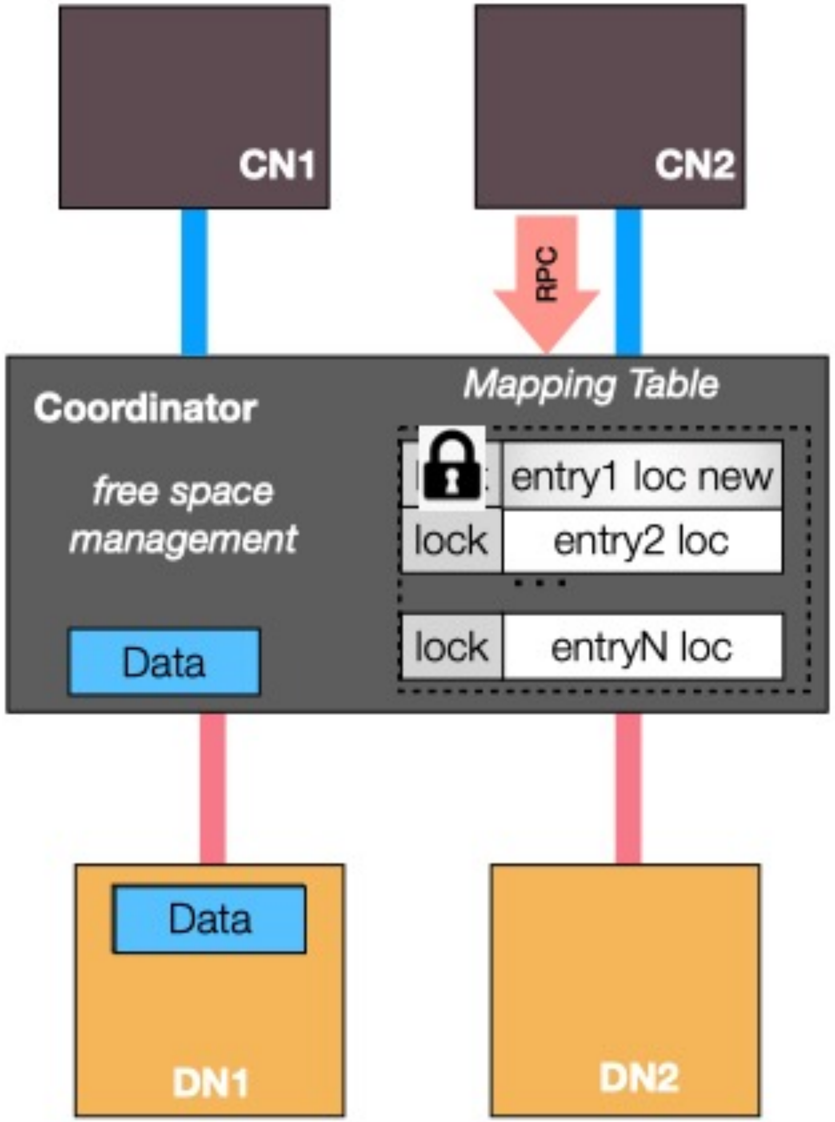
Read Flow

- CN sends RPC to Coordinator
- Coordinator locks the entry in mapping table
- Coordinator reads data from DN and then replies to CN

pDPM-Central



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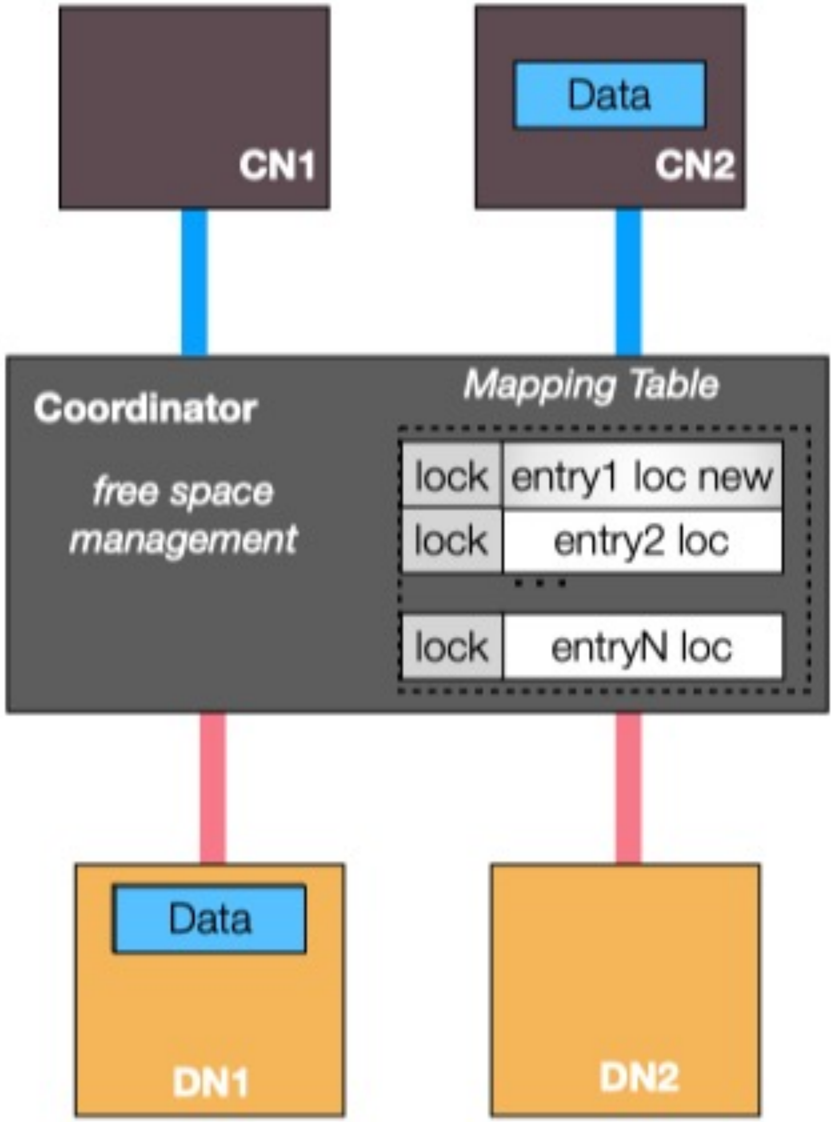
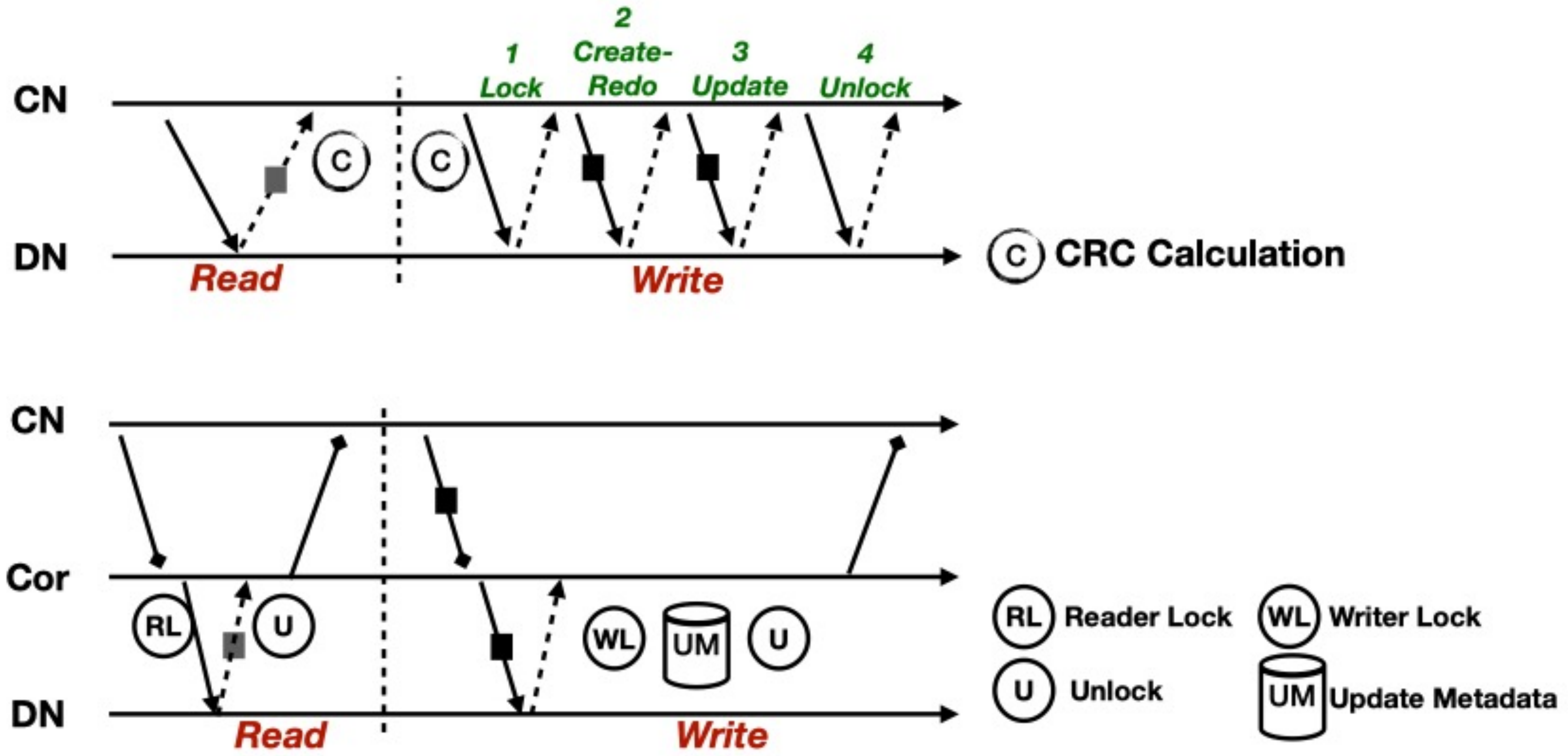
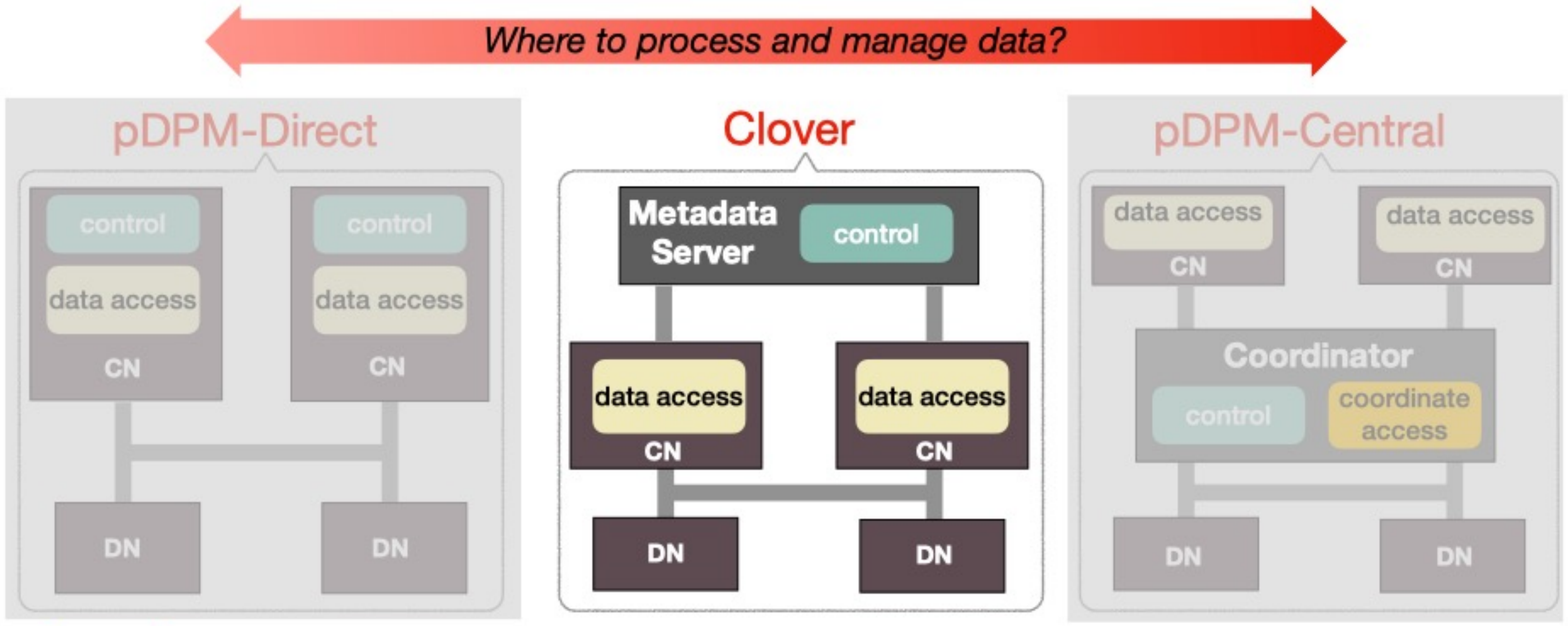
All cases
Read: 2 RTTs
Write: 2 RTTs

Slower read
Poor scalability: coordinator is the bottleneck



pDPM-Direct/Central RW Protocols





- Slow write
- Slow for large data

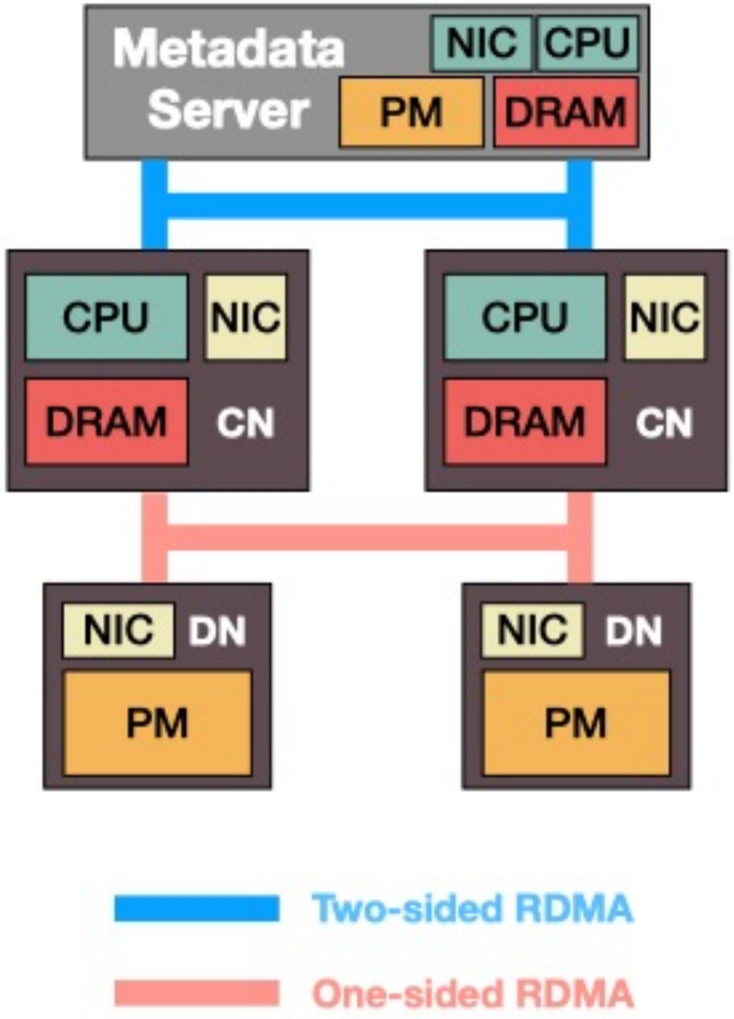
Distributed data & metadata planes

Separate data & metadata planes

- Extra read RTTs
- Coordinator cannot scale

Centralized data & metadata planes

Clover: Combining Distributed and Centralized Approaches



High-level idea: separate data and metadata plane

- Separate locations
- Different communication methods
- Different management strategy

Data Plane

- `CNs` directly access `DNs` with one-sided RDMA

Metadata Plane

- `CNs` talk to metadata server (`MS`) with two-sided RDMA

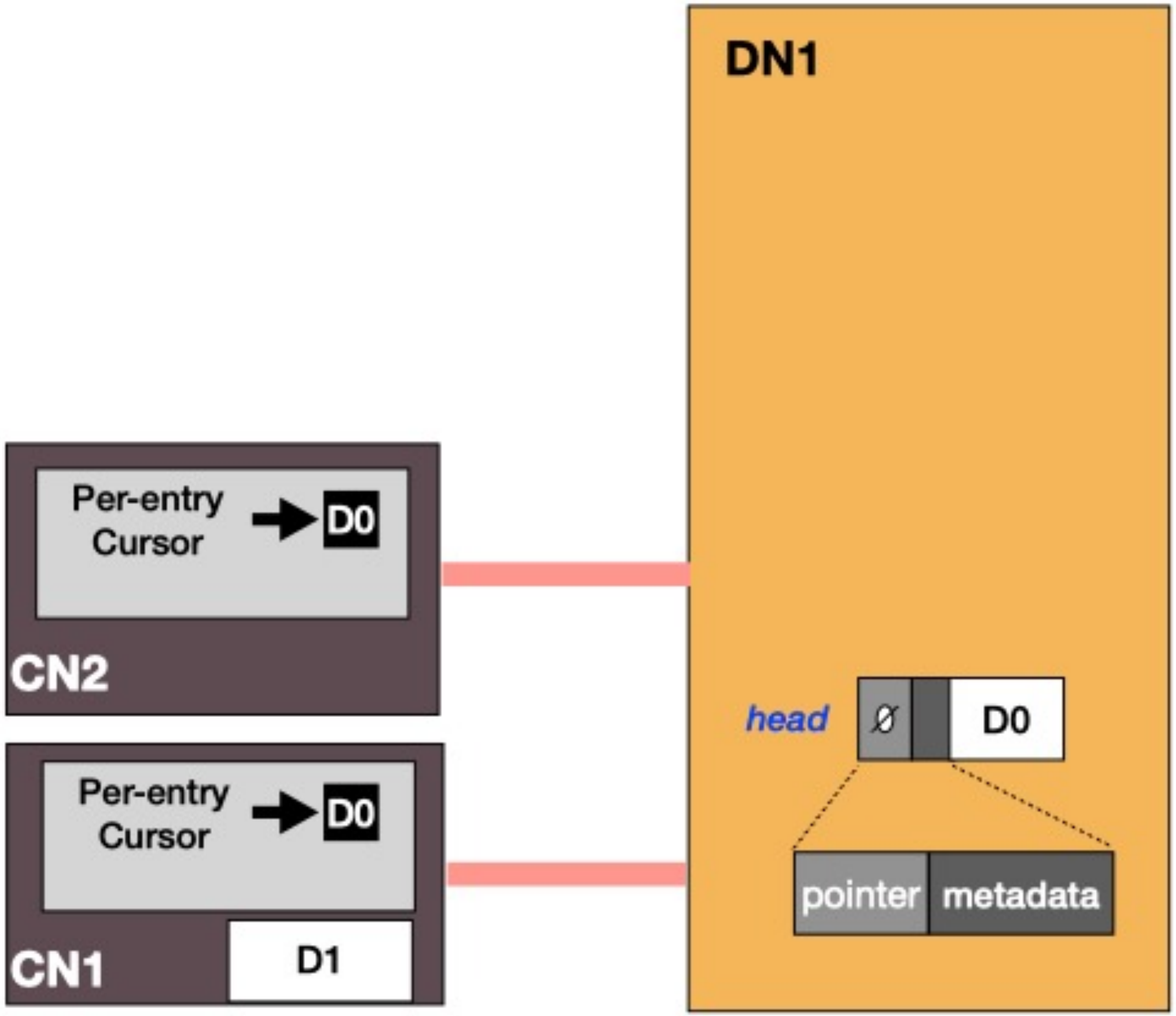
Main Challenge in Data Plane:

How to efficiently support concurrent data accesses from CNs to DNs?

Our Approaches:

- Lock-free data structures for un-orchestrated concurrent accesses
- Optimizations to further reduce read/write RTTs

➡ Guarantees ***read committed*** and ***atomic write***

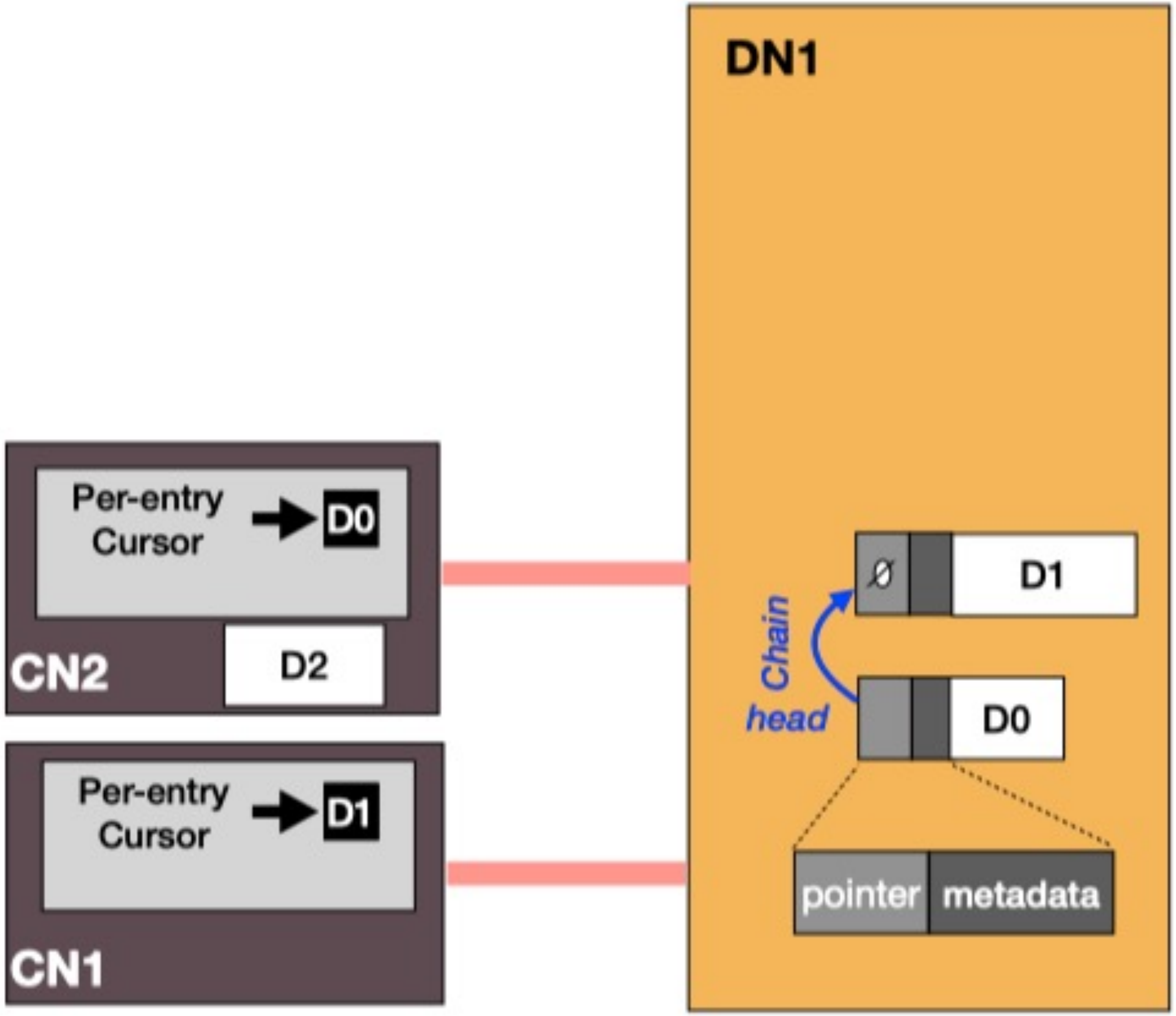


Lock-free data structures

Chained redo copies (versions) at `DNs`
`CNs` cache a ***cursor*** that points to a version

Write Flow

1. Out-of-place write (create redo copy)
2. Chain the redo-copy, using ***`c&s`***
3. If 2. fails, update cursor and retry



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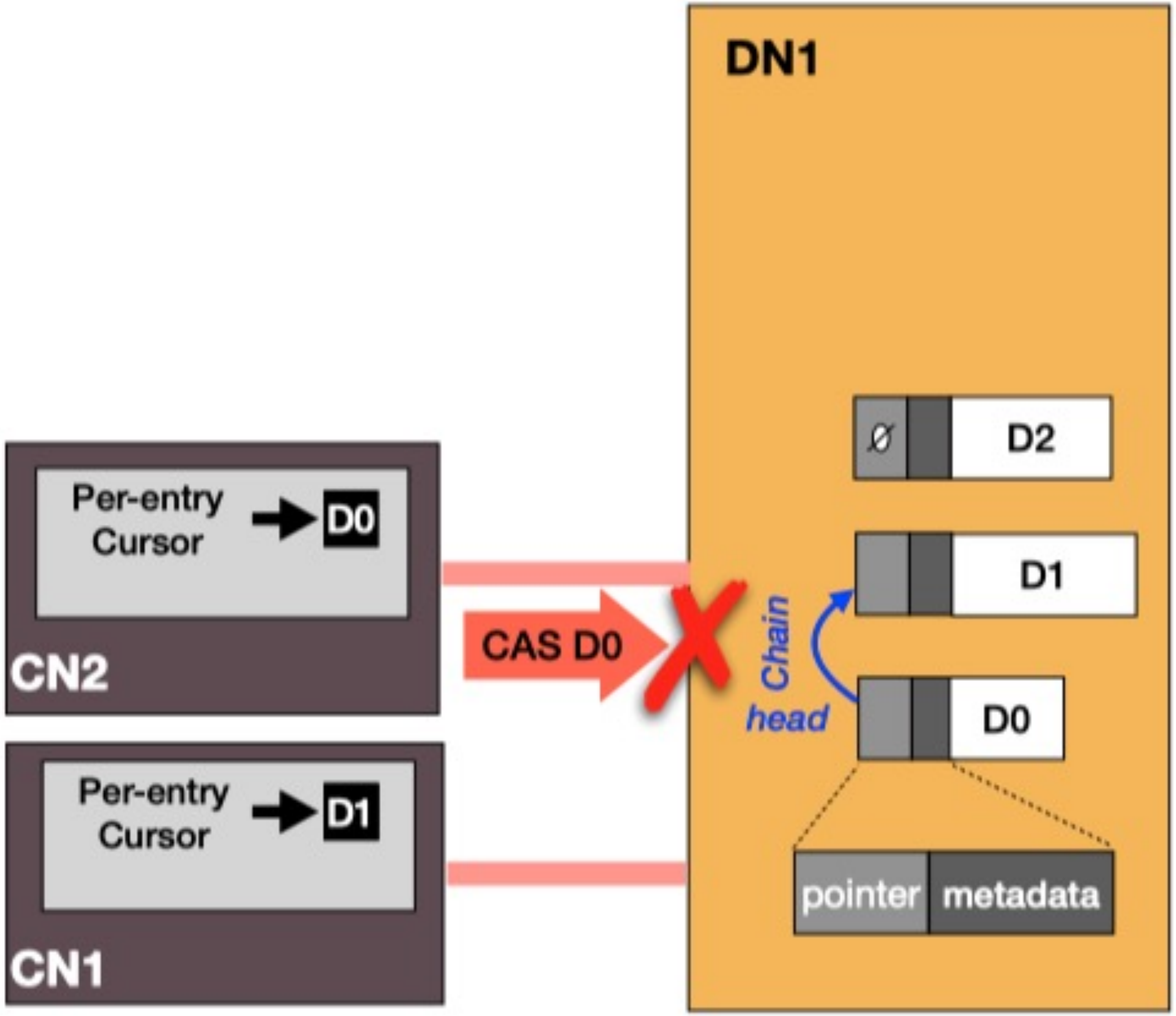

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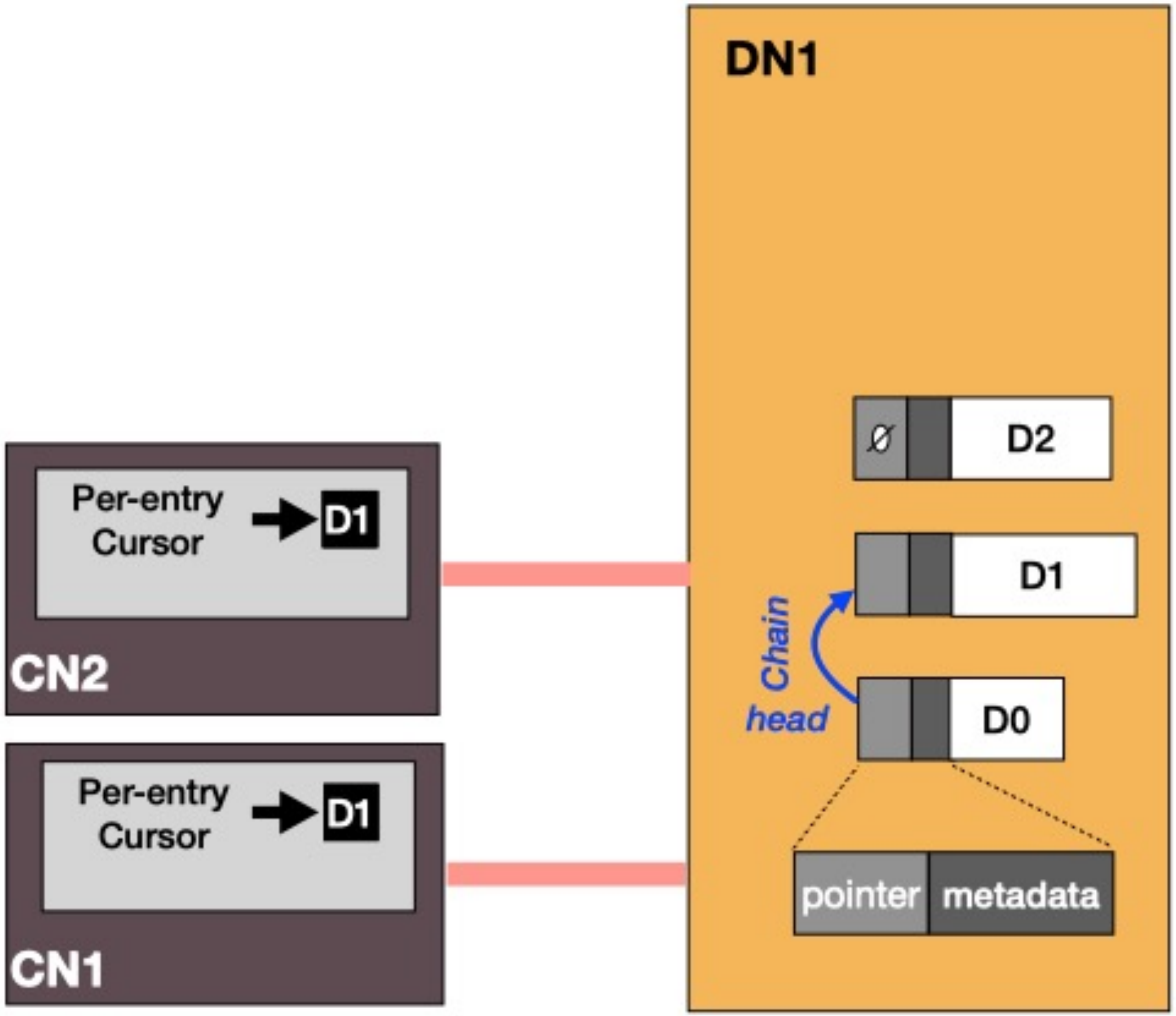

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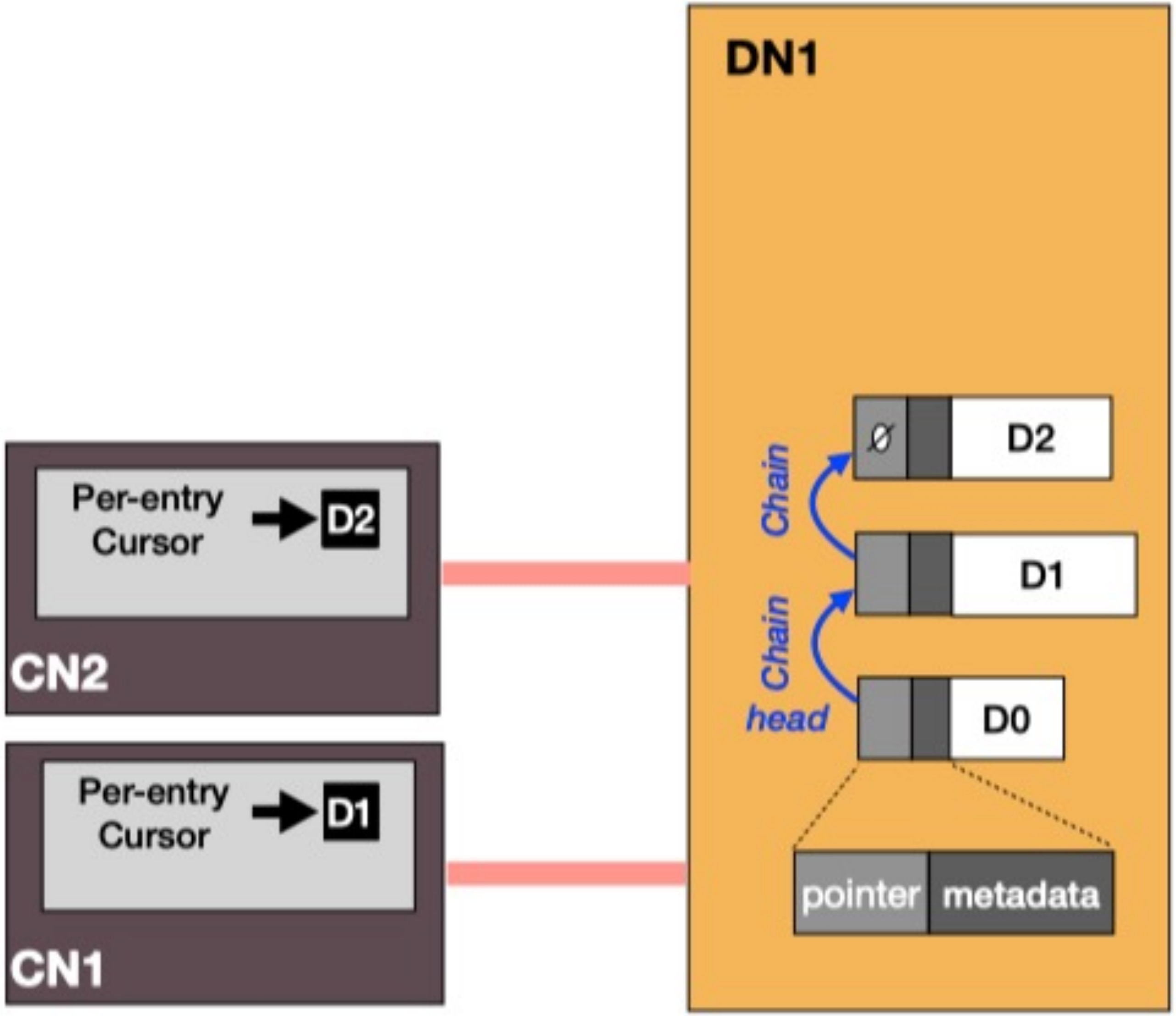

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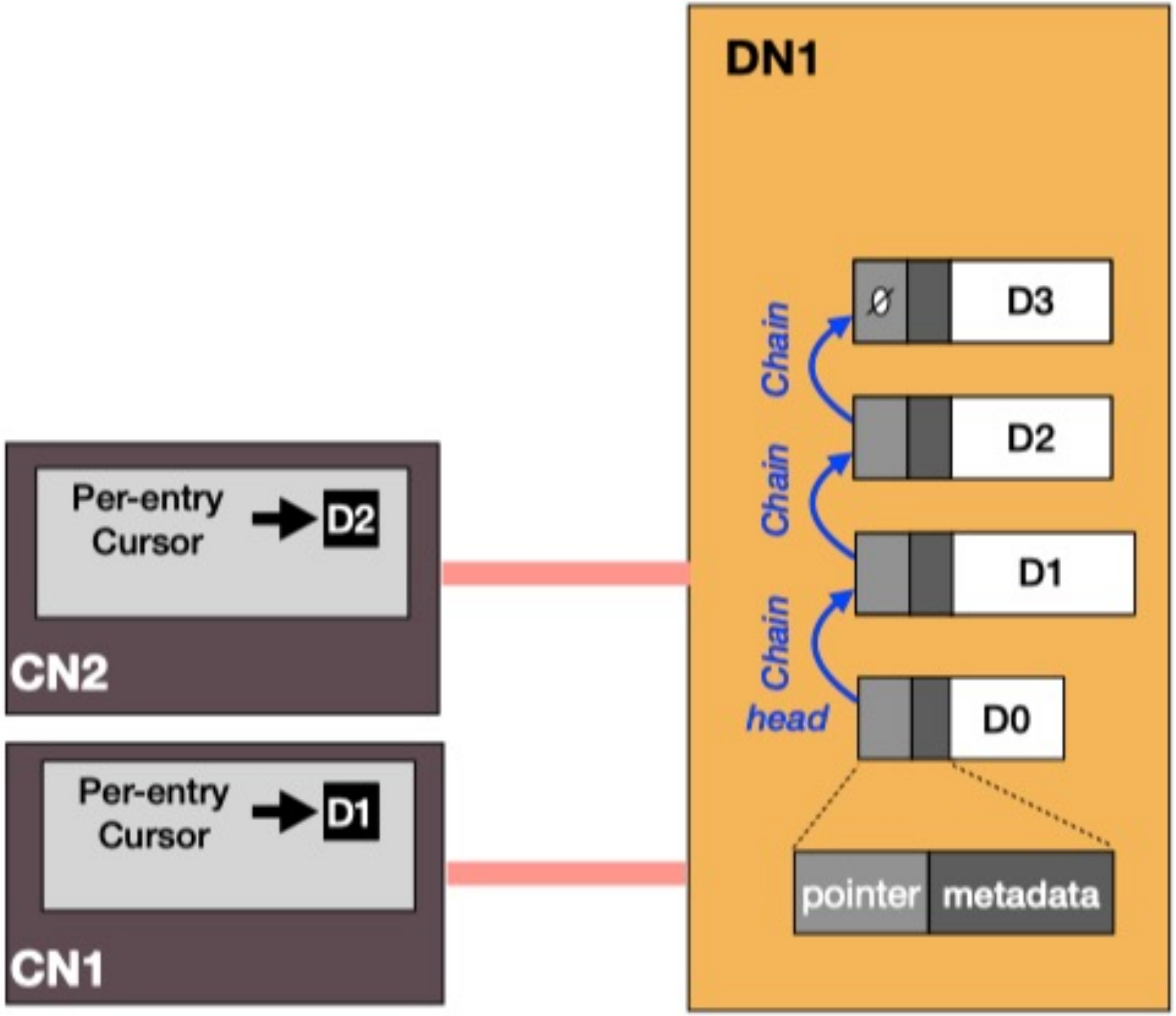

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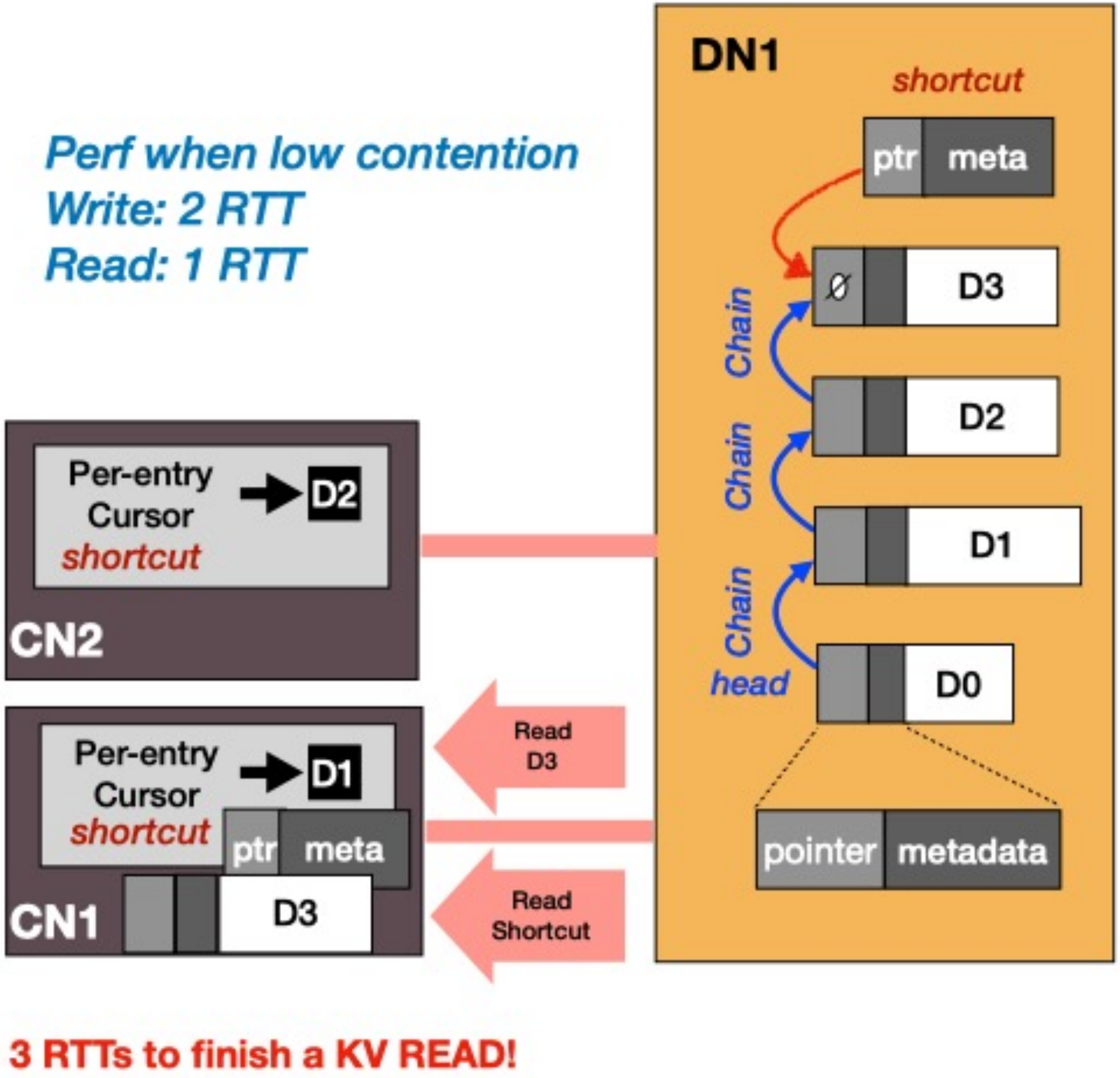

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Optimization: Shortcut

Uses a shortcut to avoid long chain walk
A shortcut at DN (mostly) points to the latest data

1. CN reads shortcut, then uses it to read data
2. CN still does cursor read in parallel

- Returns when the faster of 1 and 2 finish

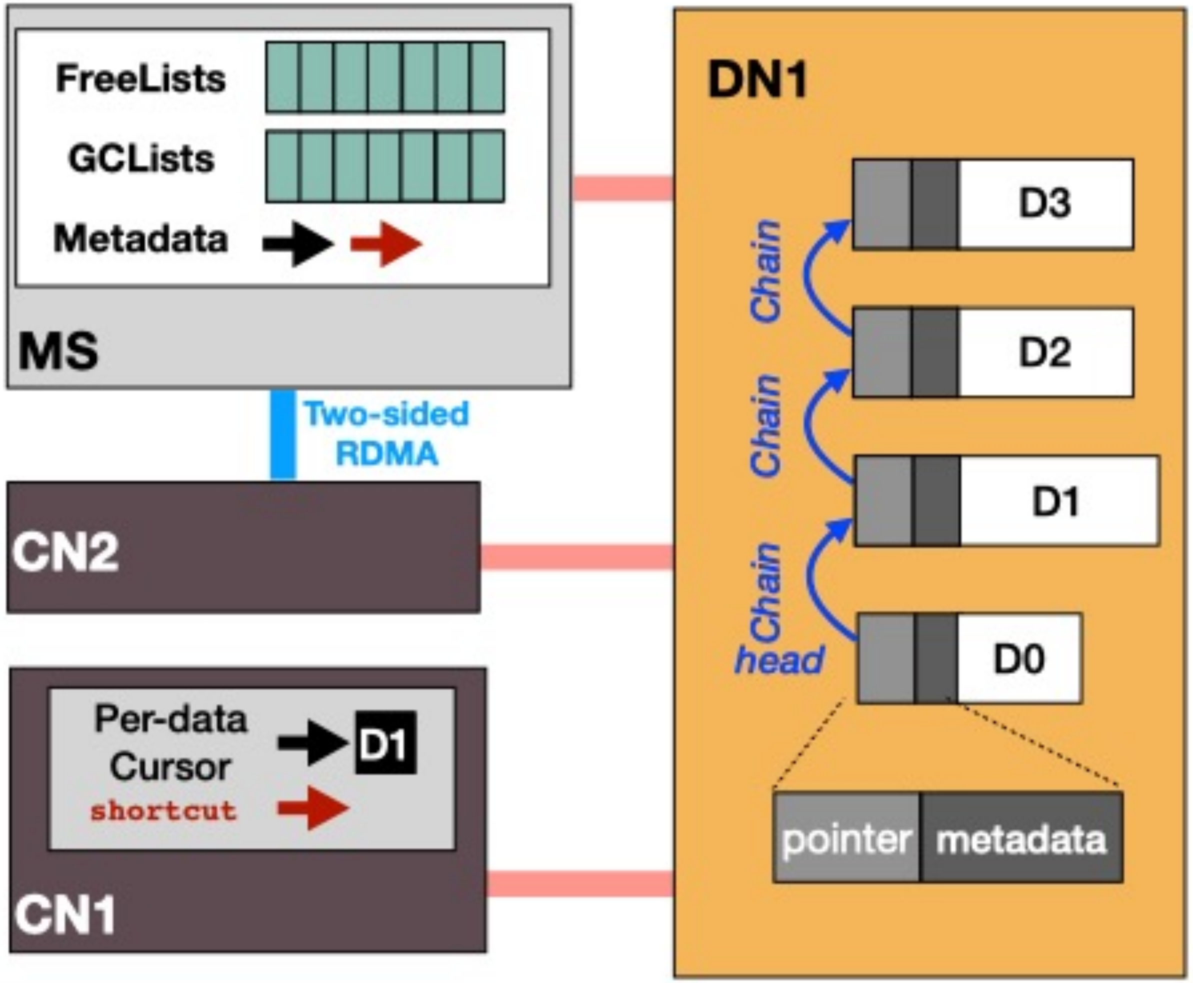
Main Challenges in Metadata Plane:

How to provide low-overhead, scalable metadata service?

Our Approaches

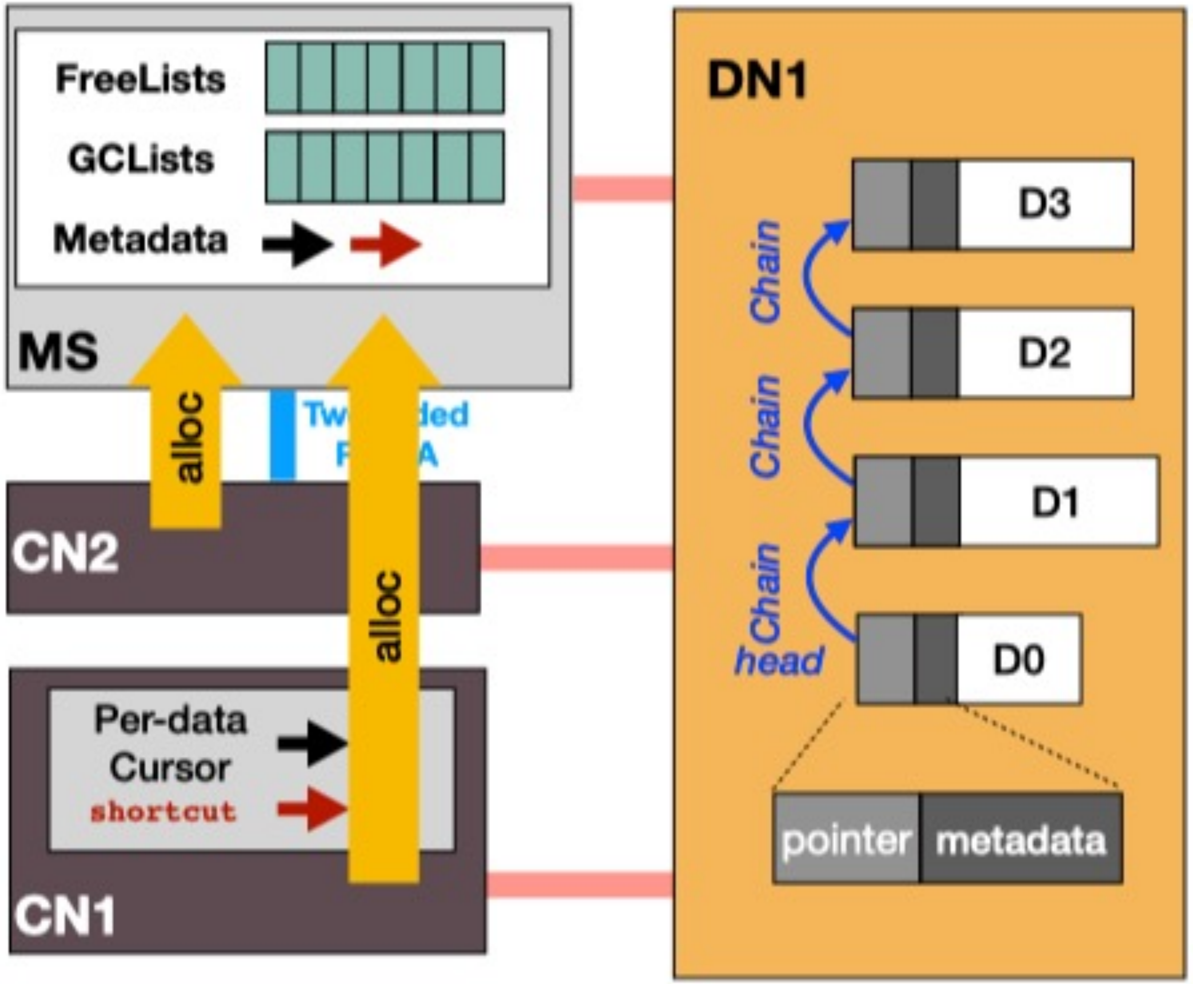
- Move ***all*** metadata operations off performance critical paths
- Batch metadata operations
- ***No*** cache invalidation

➡ No performance overhead caused by metadata ops (common case)



Metadata Server (MS)

- Space management
- Garbage collection
- Global load balancing



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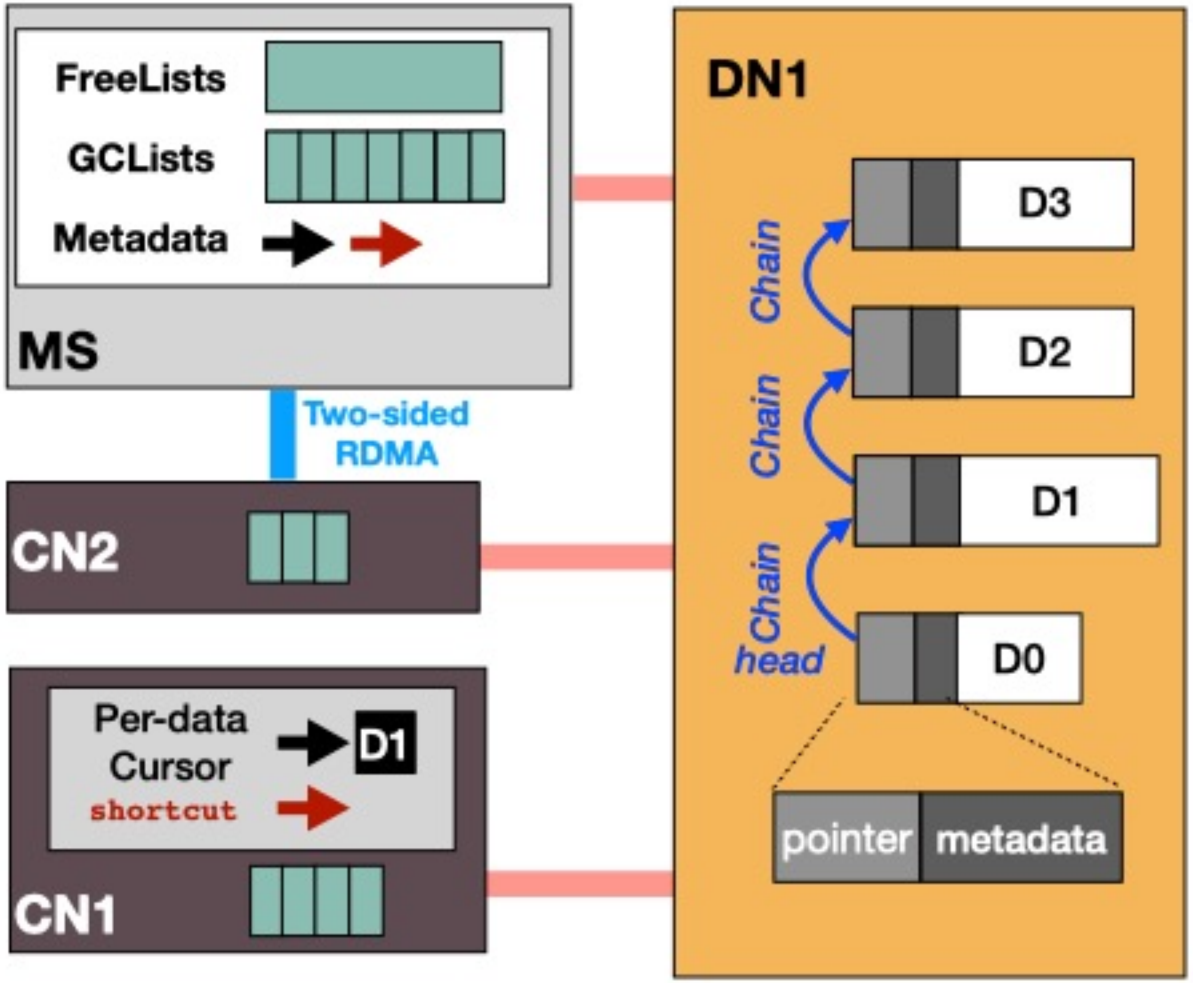
- MS assigns spaces from FreeLists (with load balancing consideration)



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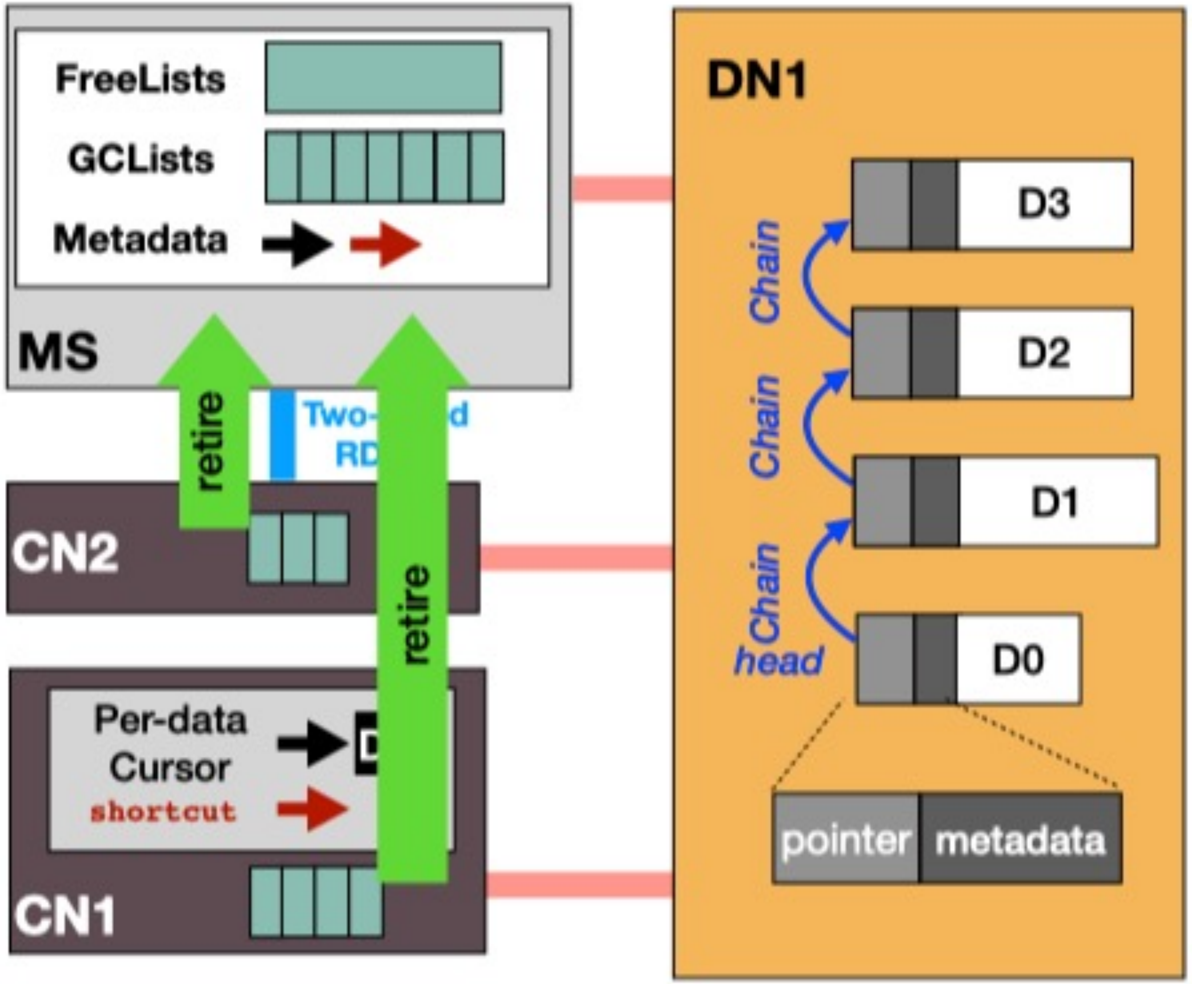

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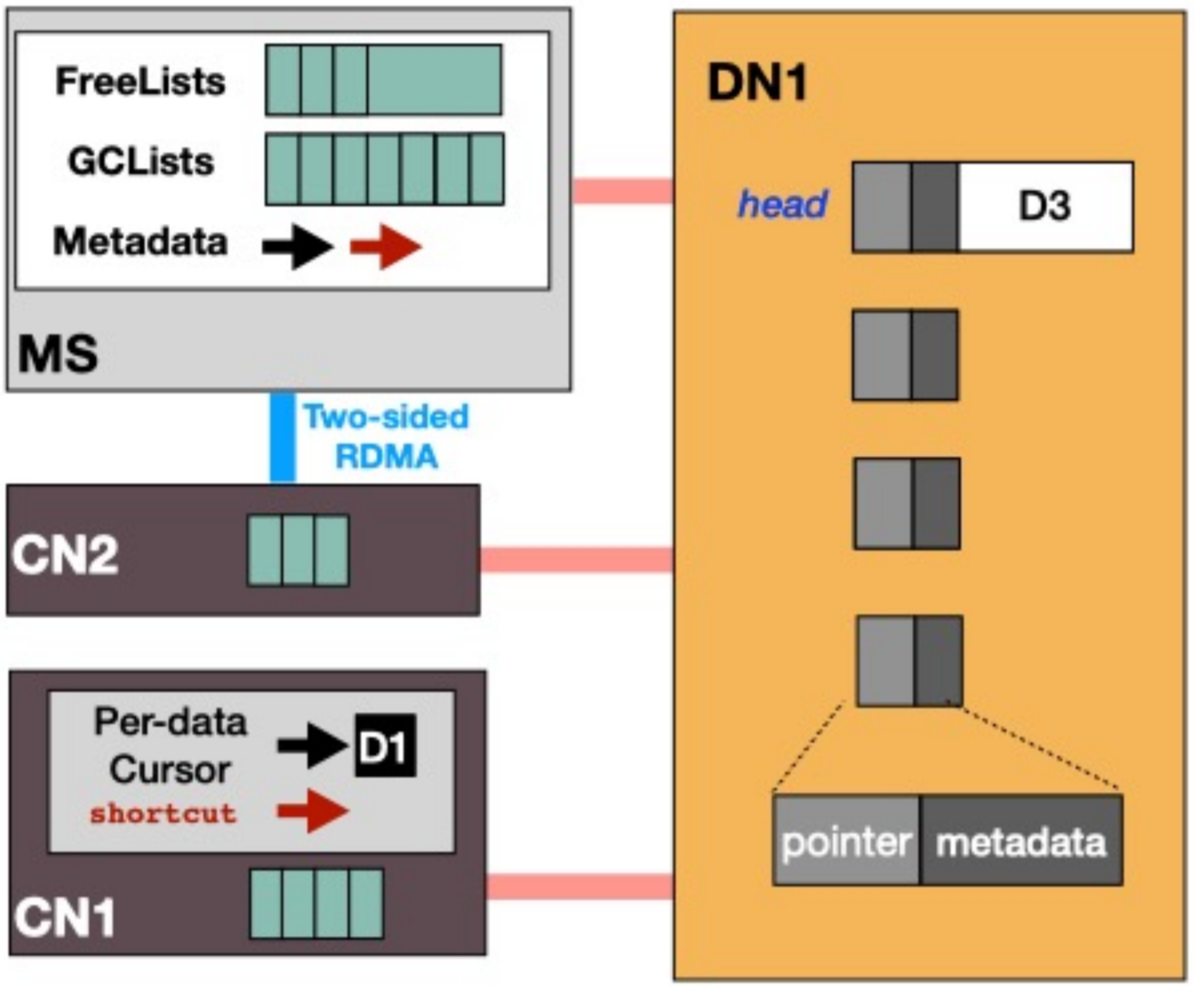
- After write, CN asynchronously ***retires*** a batch of old versions
- MS enqueues them into FreeLists



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Challenge in GC part

- How to reduce communication via network between MS and CN?
  - Never notify other CN their cursor should be invalid after GC.
- When GC is taking effect, the outdated cursor might lead to cursor walking failure?
  - Write-back like & Use `GC-version`.
- How to guarantee read isolation and atomicity?
  - Set read timeout scheme.
- How to solve GC-version overflow problem?
  - Restart it to Zero.

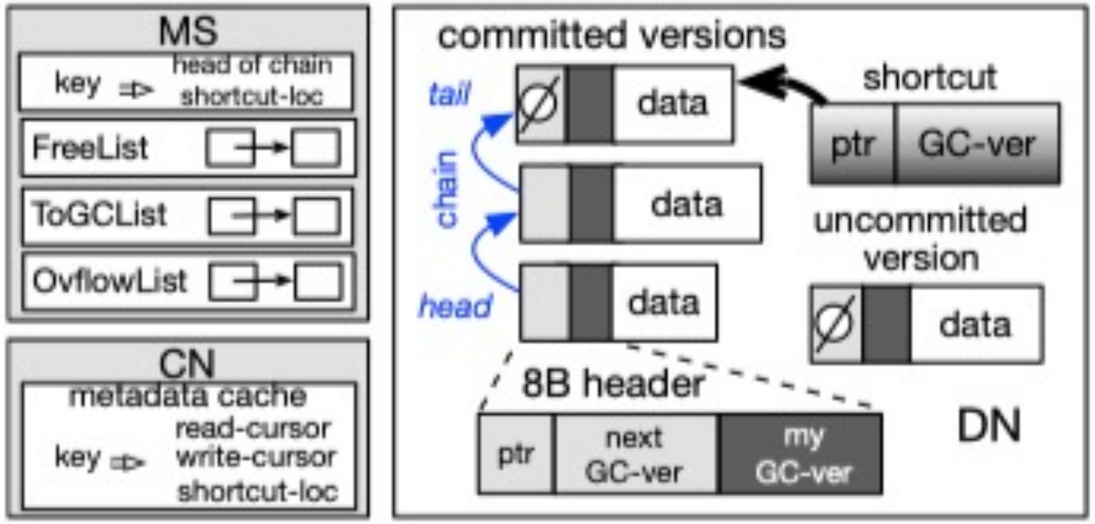


Figure 3: Clover System Design.

Clover RW Protocols

Reliability and Load Balancing

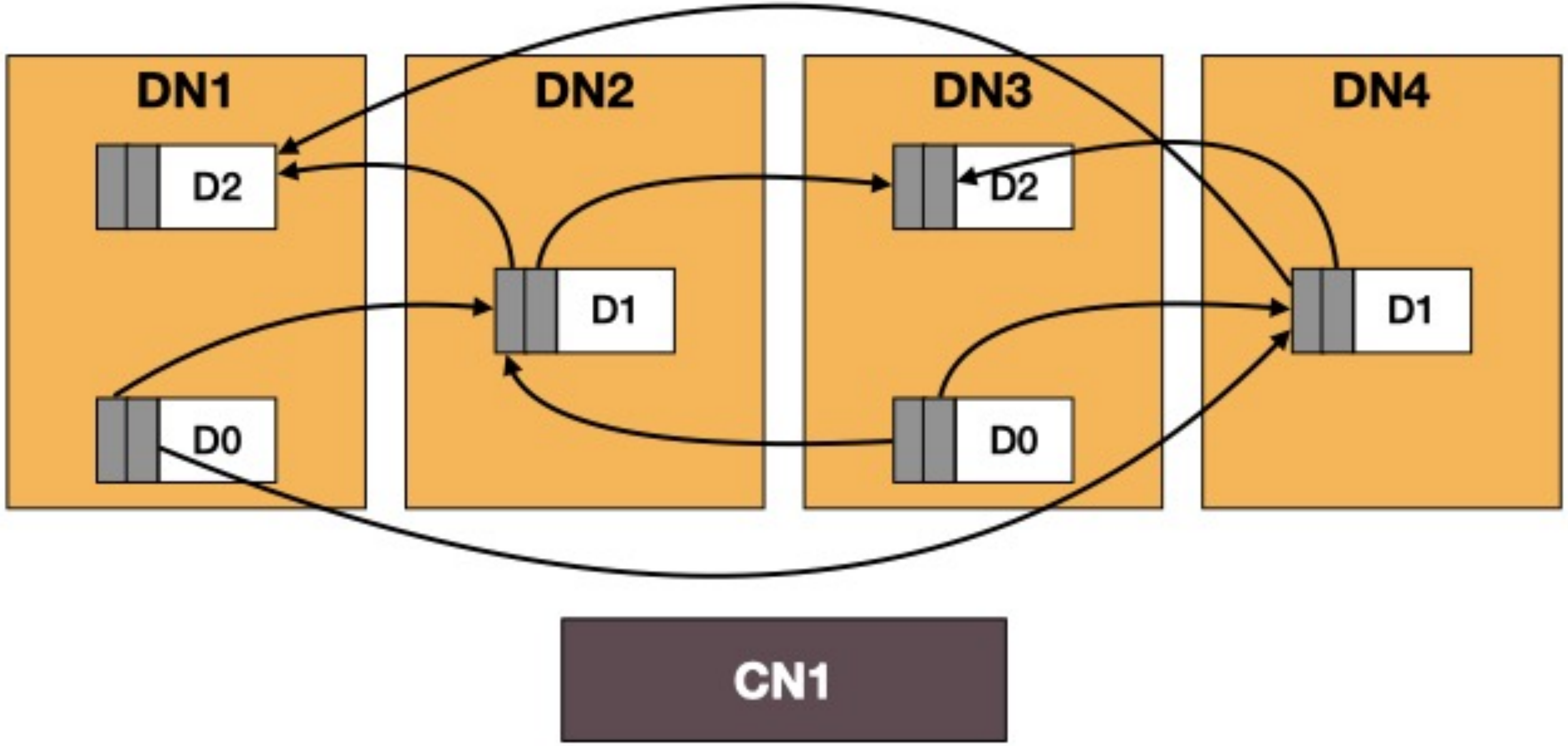
Data reliability through a novel chaining replication

- Link a version to all the replicas of next version

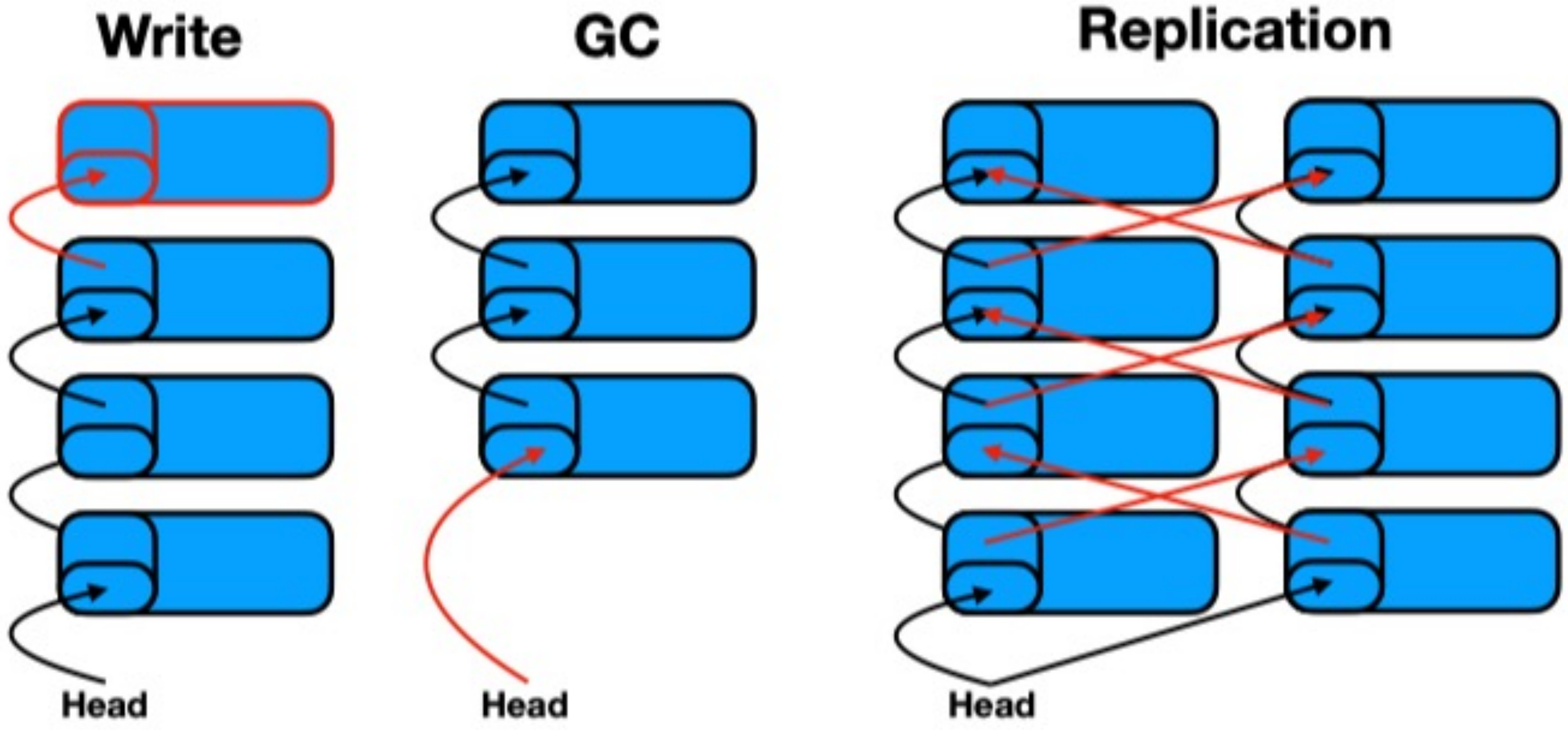
Metadata reliability through shadow MS servers

Load balancing via a two-level approach

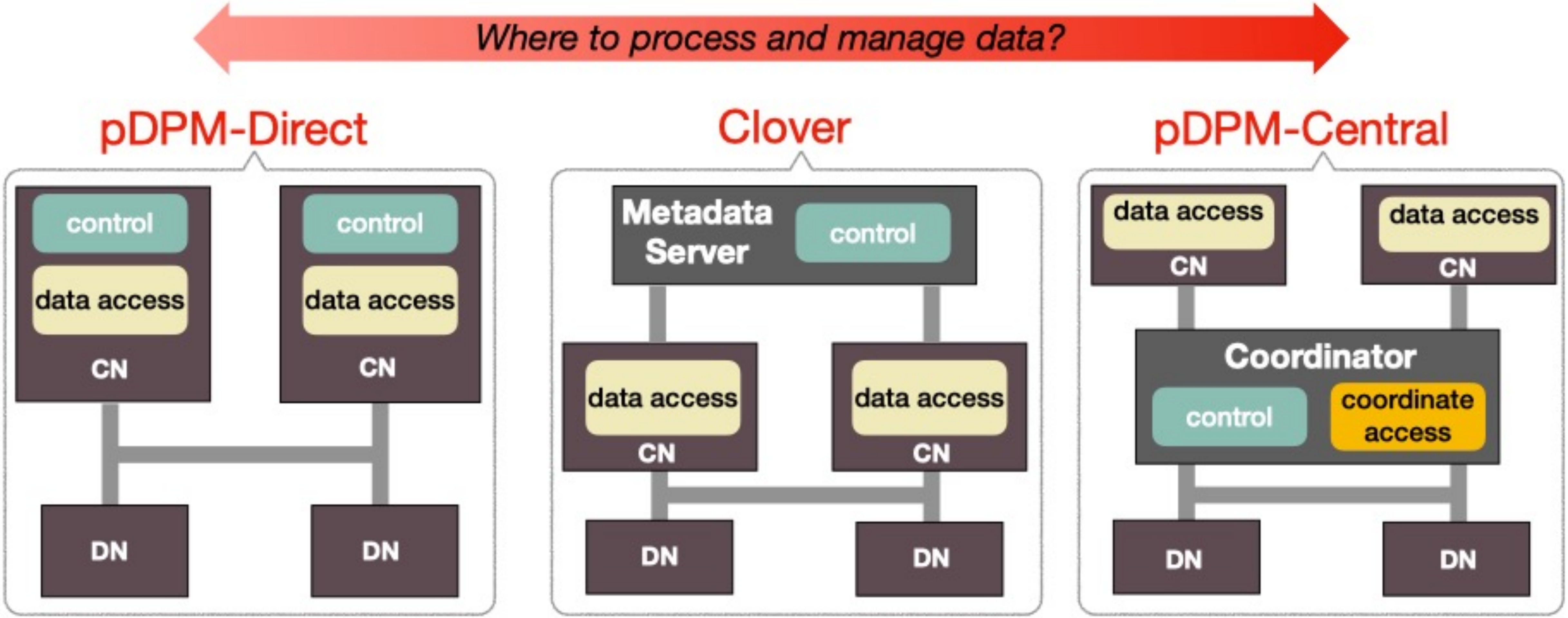
- MS and CNs both control location
- Versions in a chain can be on different DNs



Clover Data Structure



Load Balancing



- Write cannot scale
- Large metadata consumption

Distributed data & metadata

+ Good read/write performance
+ Scale with both CNs and DNs

Separate data & metadata

- Extra read RTTs
- Coordinator cannot scale

Centralized data & metadata

Where is the key-value hashtable?

- pDPM-Direct: each CN has an identical mapping table
- pDPM-Central: each CN performs CN->coordinator mapping. Each coordinator has a full identical mapping table
- Clover: MSs have full mapping table, each CN caches a portion of it

Evaluation Setup

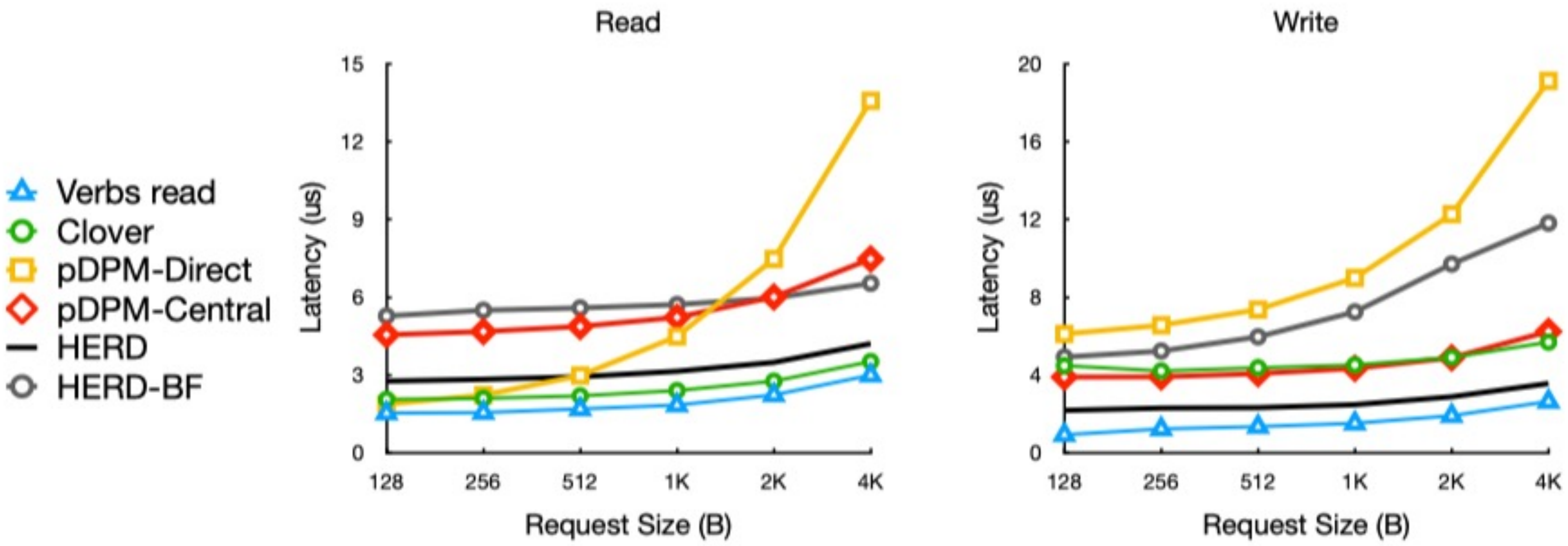
Systems evaluated

- ***pDPM systems***: pDPM-Direct, pDPM-Central, Clover
- ***Non-disaggregated PM systems***: Octopus [ATC'17] and Hotpot [SoCC'17]
- ***Two-sided KVS***: HERD [SIGCOMM'14] (also ported to BlueField SmartNIC, HERD-BF)

Testbed

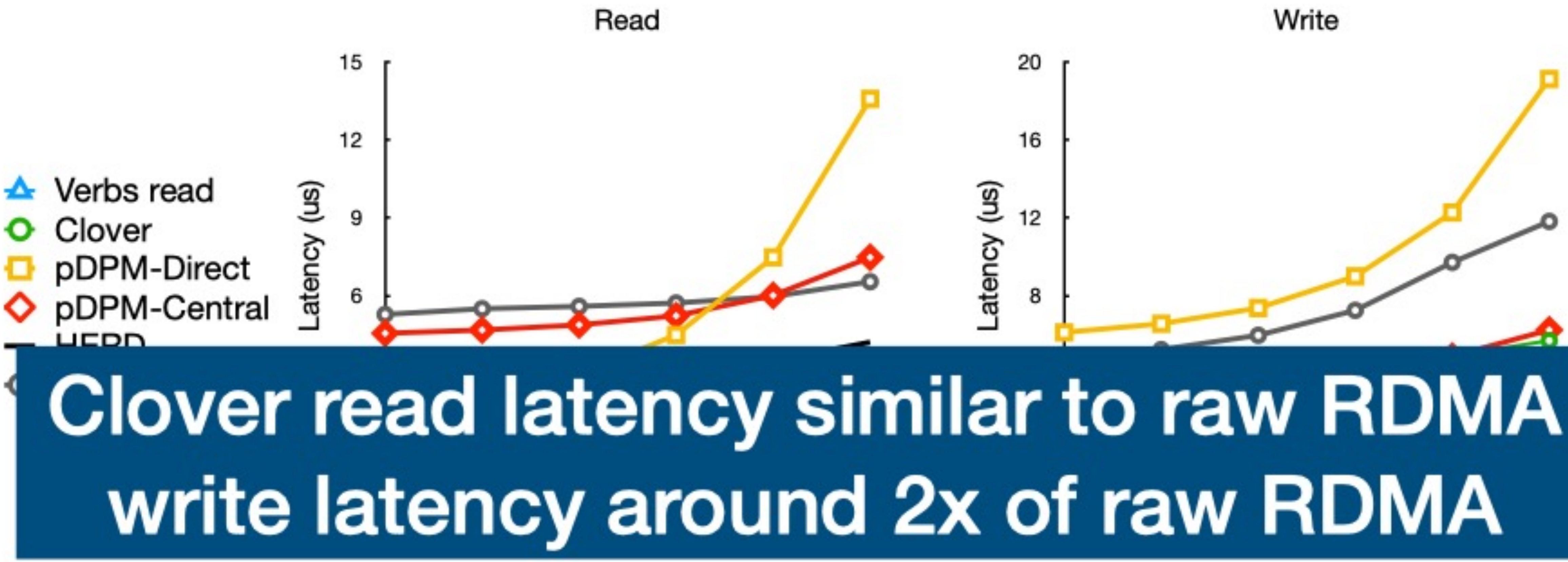
- 14 servers, each with a 100Gbps RDMA NIC, connected via a 100Gbps IB switch
- DRAM as emulated PM

Microbenchmark - Latency



- One CN synchronously reads/writes a KV entry on a DN
- HERD and HERD-BF use 12 polling threads

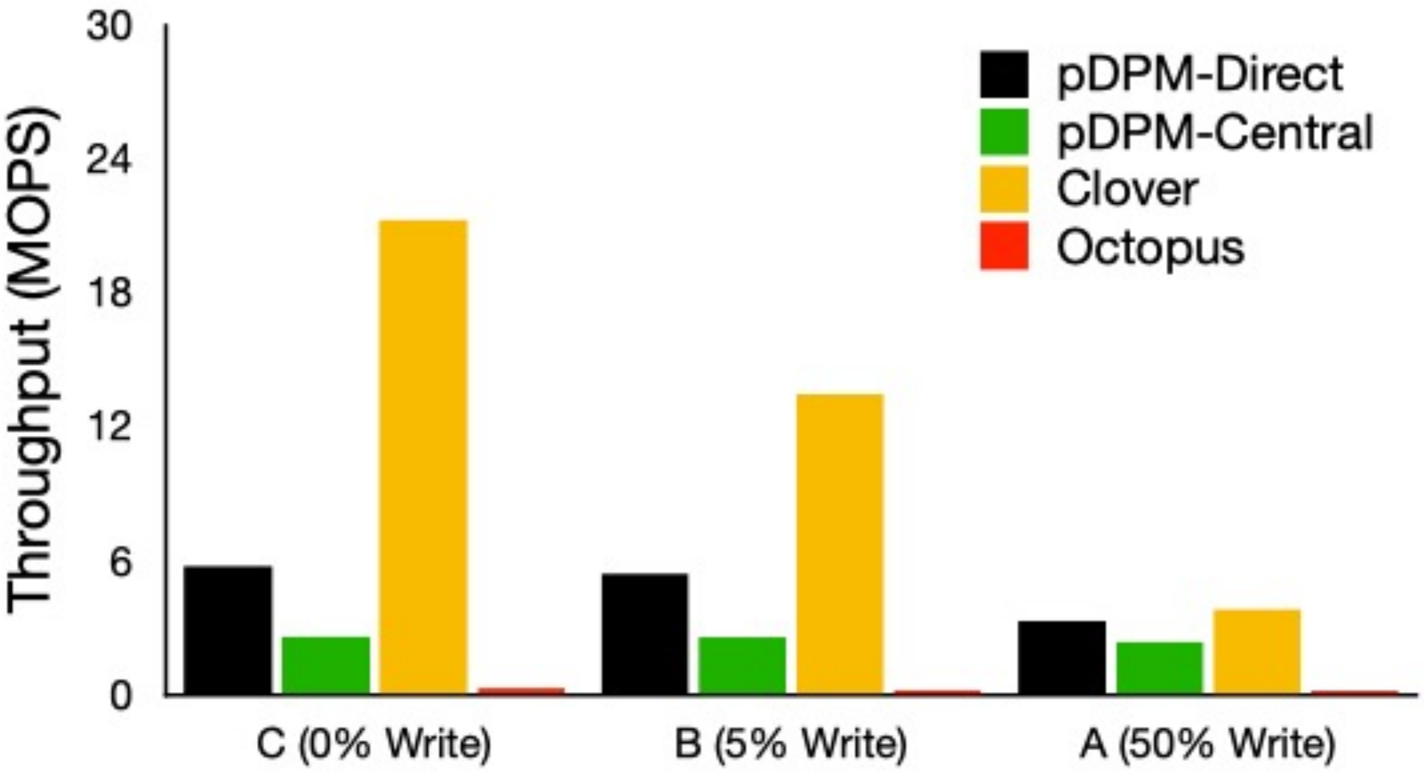
Microbenchmark - Latency



Clover read latency similar to raw RDMA write latency around 2x of raw RDMA

- One CN synchronously reads/writes a KV entry on a DN
- HERD and HERD-BF use 12 polling threads

YCSB Results



- 100K KV entries, 1 million operations, Zipf access distribution
- 4 CNs (8 threads per CN), 4 DNs

YCSB Results

Clover outperforms non-disaggregated PM systems and is similar to aDPM under common cases (worse under heavy concurrent writes)

- 100K KV entries, 1 million operations, Zipf access distribution
- 4 CNs (8 threads per CN), 4 DNs

YCSB Results

Clover is cheap to build and run

and is similar to aDPM under common cases (worse under heavy concurrent writes)

- 100K KV entries, 1 million operations, Zipf access distribution
- 4 CNs (8 threads per CN), 4 DNs

Conclusion

- pDPM offers deployment, cost, and performance benefits
- Cleanly separating data and metadata is crucial but not easy
- Our pDPM findings could also apply to disaggregated DRAM
- pDPM performs worse under high write contention or complex ops
- Future system could benefit from a hybrid disaggregation model

Possible Questions

- If DPM-Central has multiple coordinates, cannot it scale?
- Why not use read-after-write to ensure remote persistency?
- Where is the key-> entry hashtable?
  - The whole table is at MS, each CN caches a portion of it?