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

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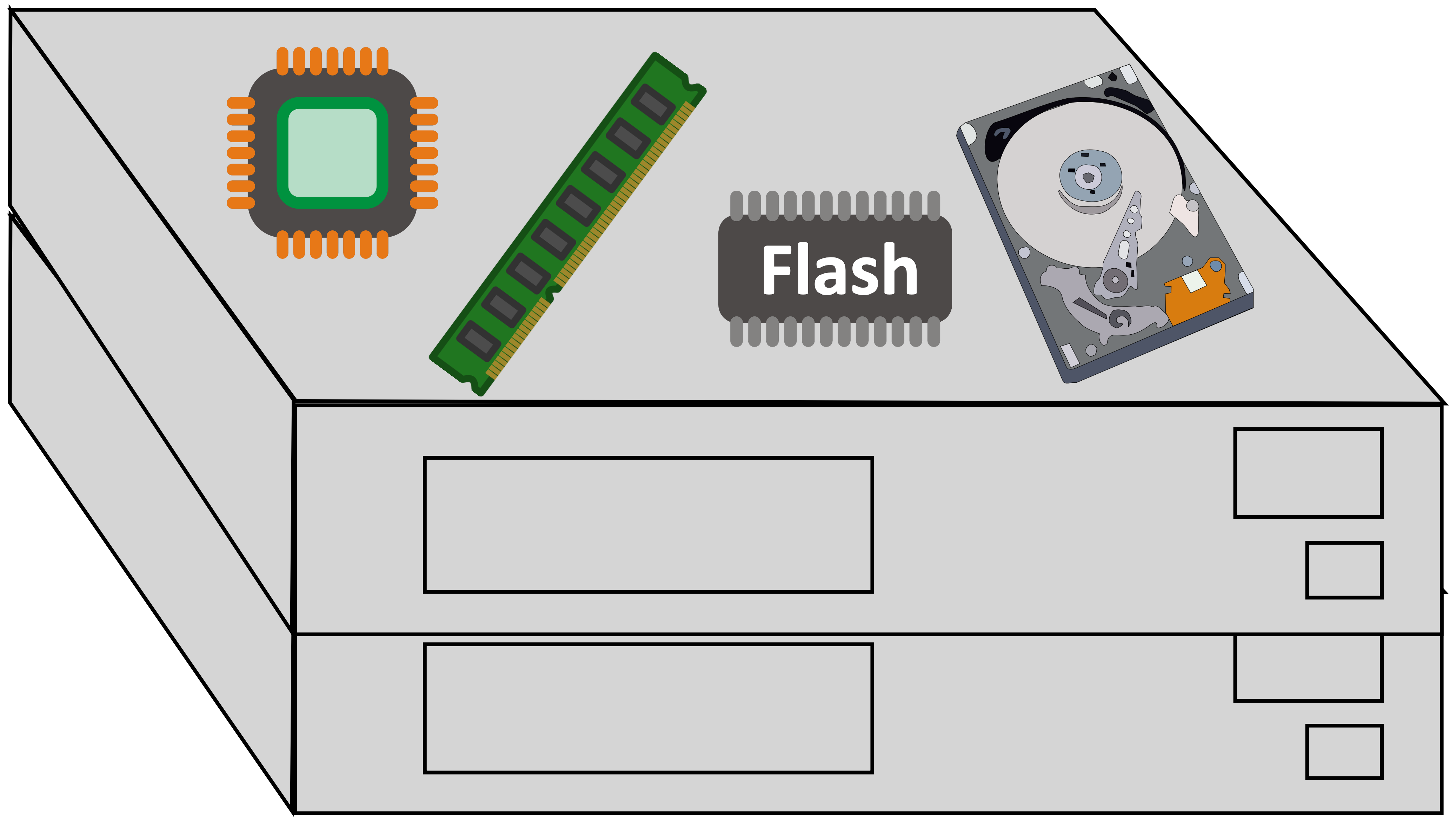
PURDUE UNIVERSITY

WukLab

UC San Diego

Resource Disaggregation

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



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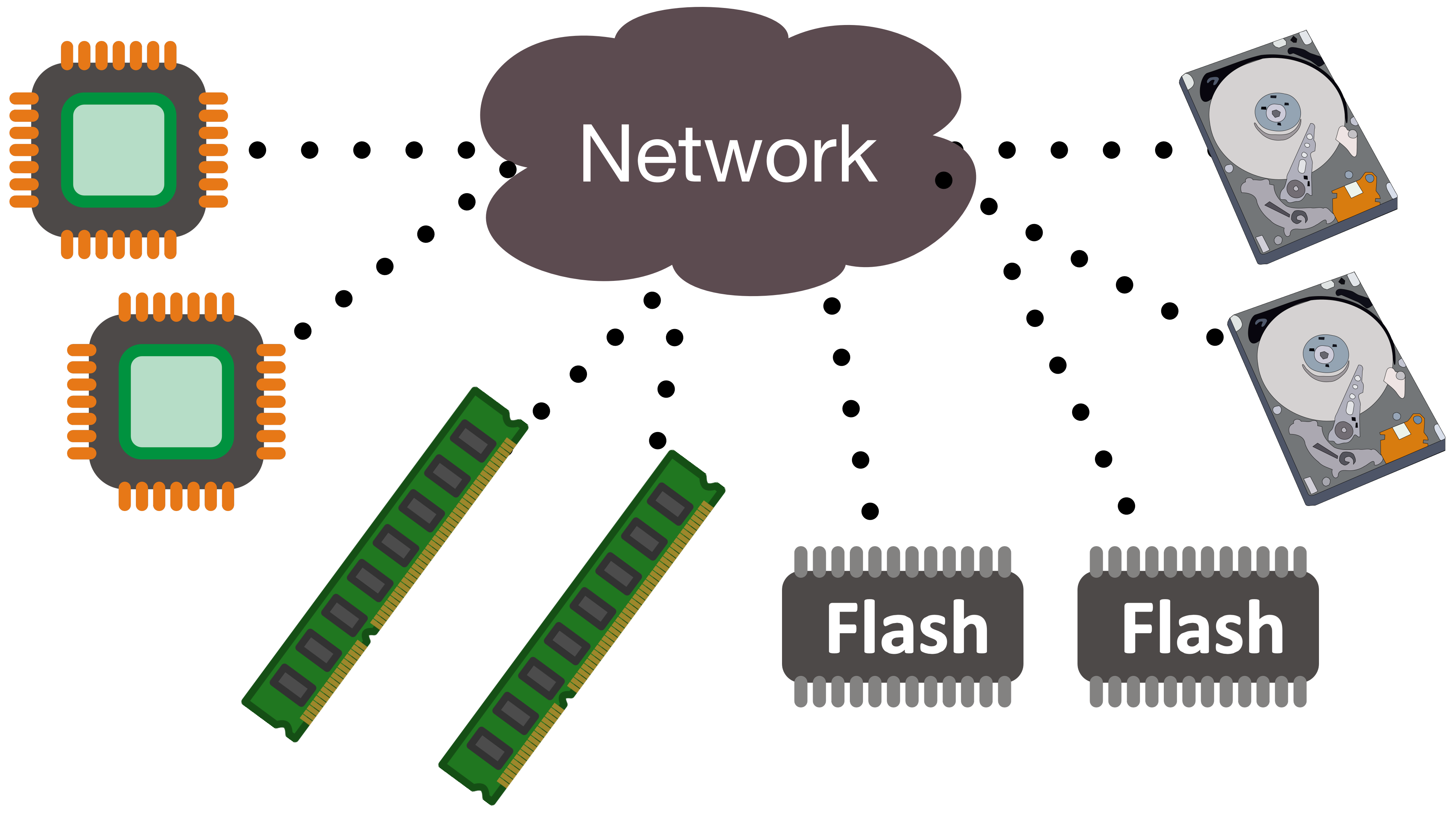

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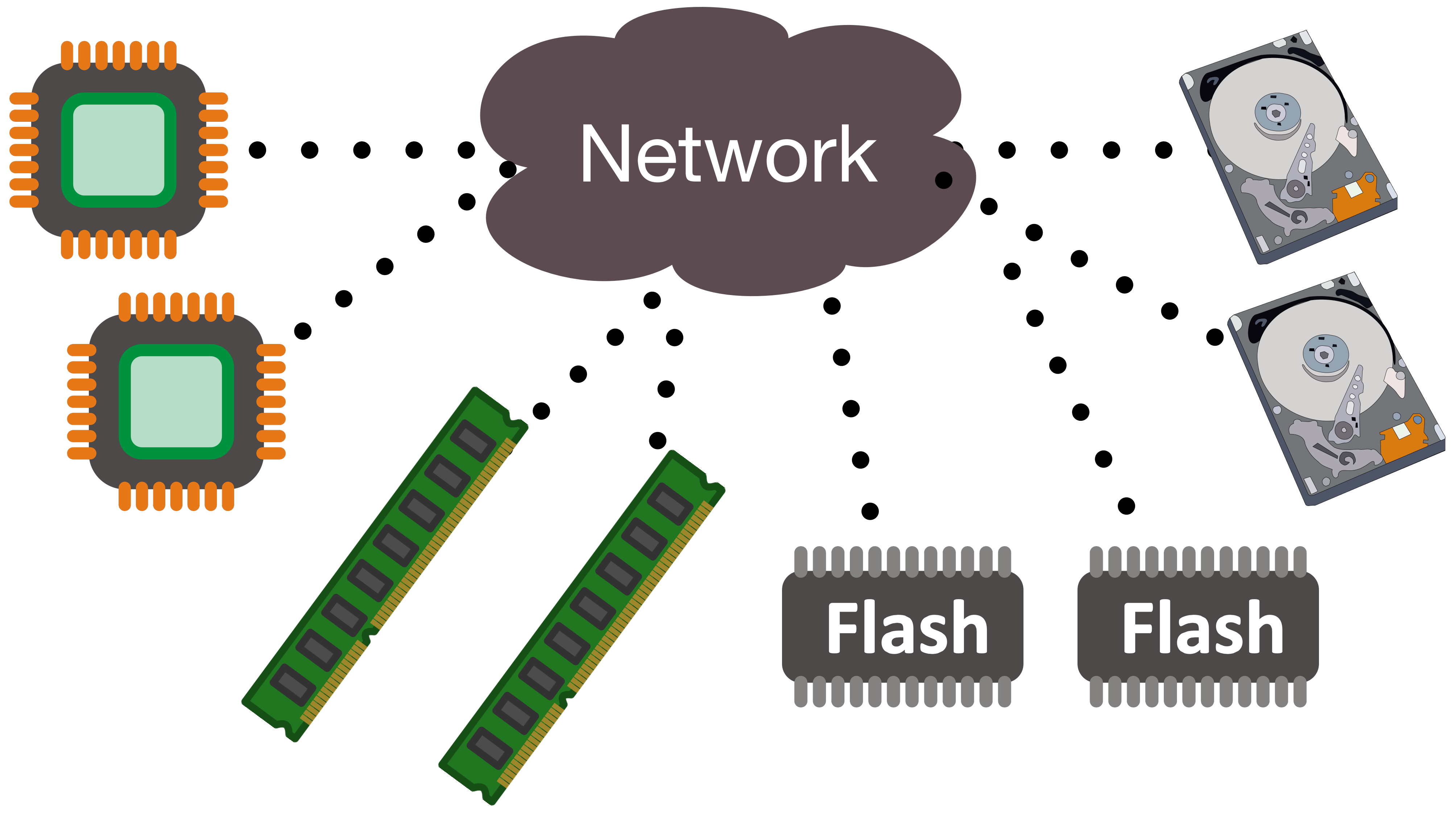
Break monolithic servers into ***network-attached*** resource pools

Better manageability, independent scaling, tight resource packing



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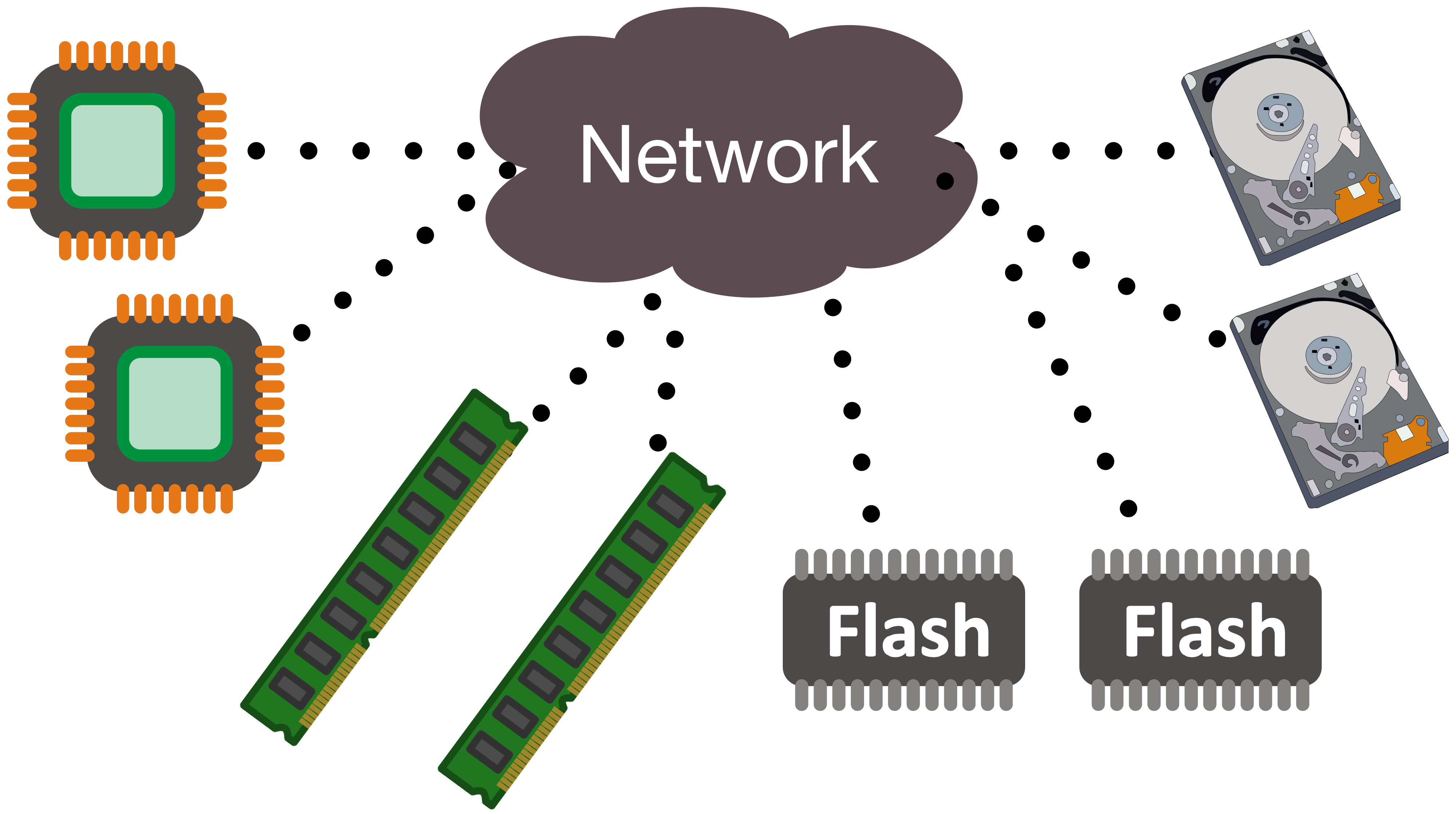
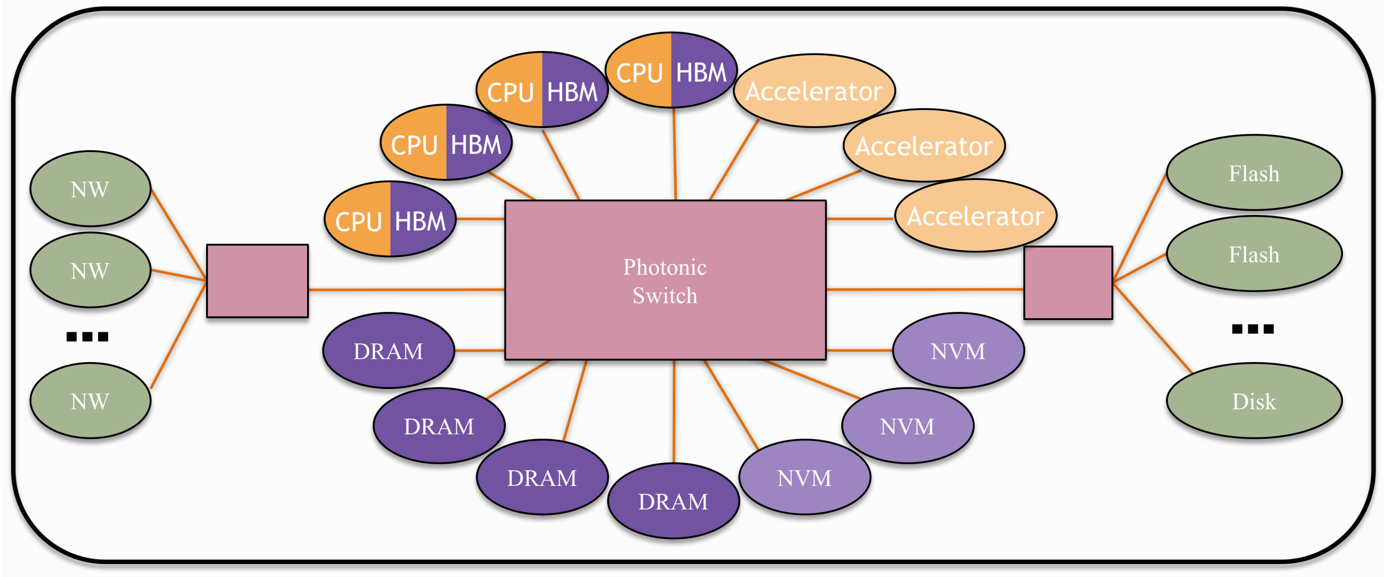
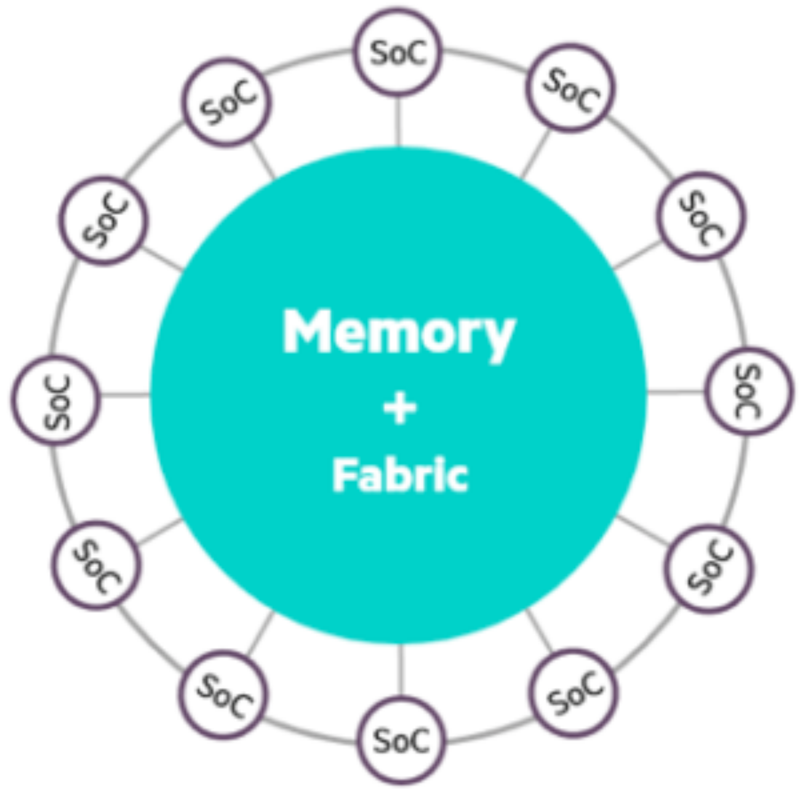


LegoOS



Berkeley Firebox



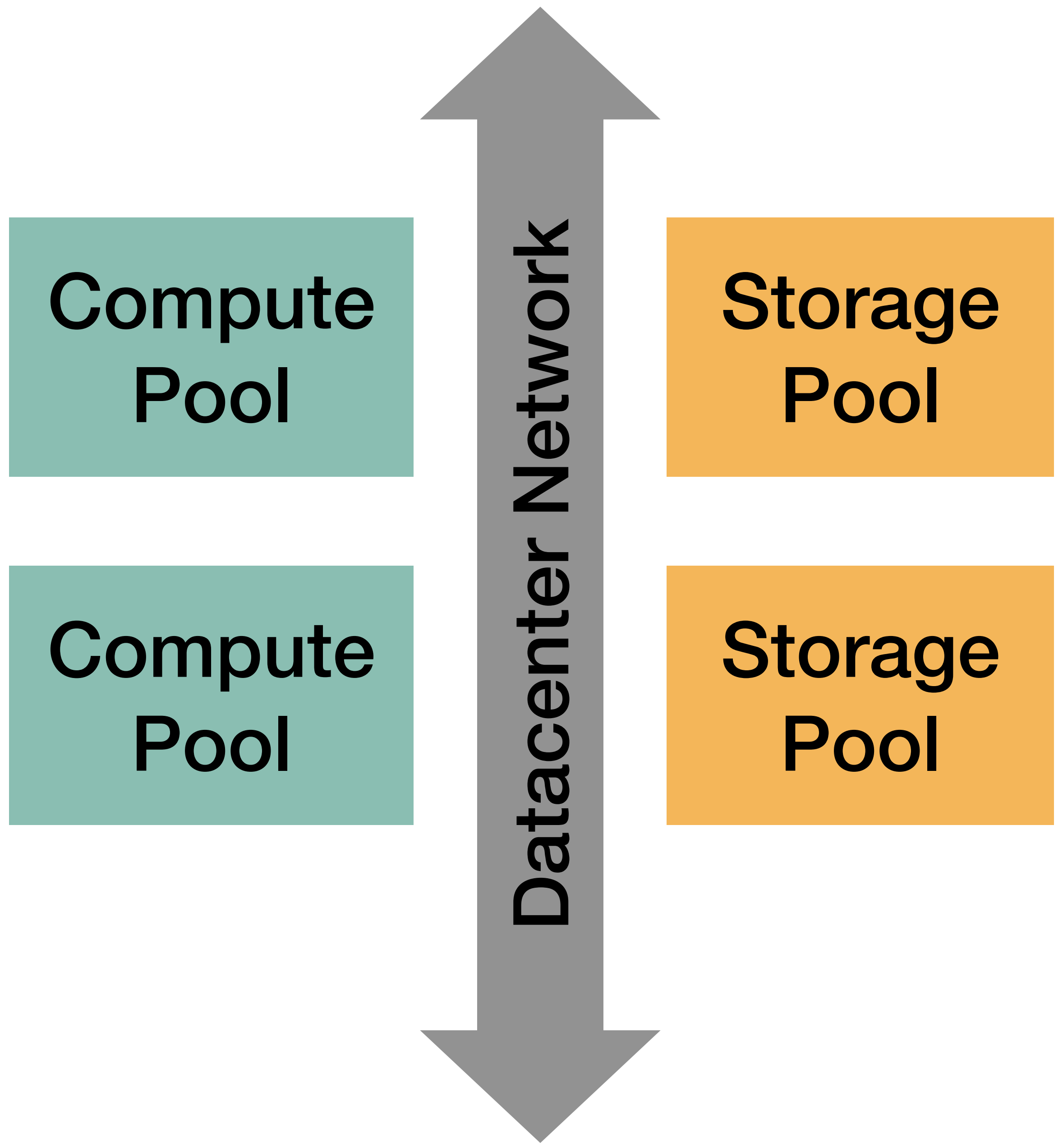
Hewlett Packard Enterprise

Disaggregated Storage

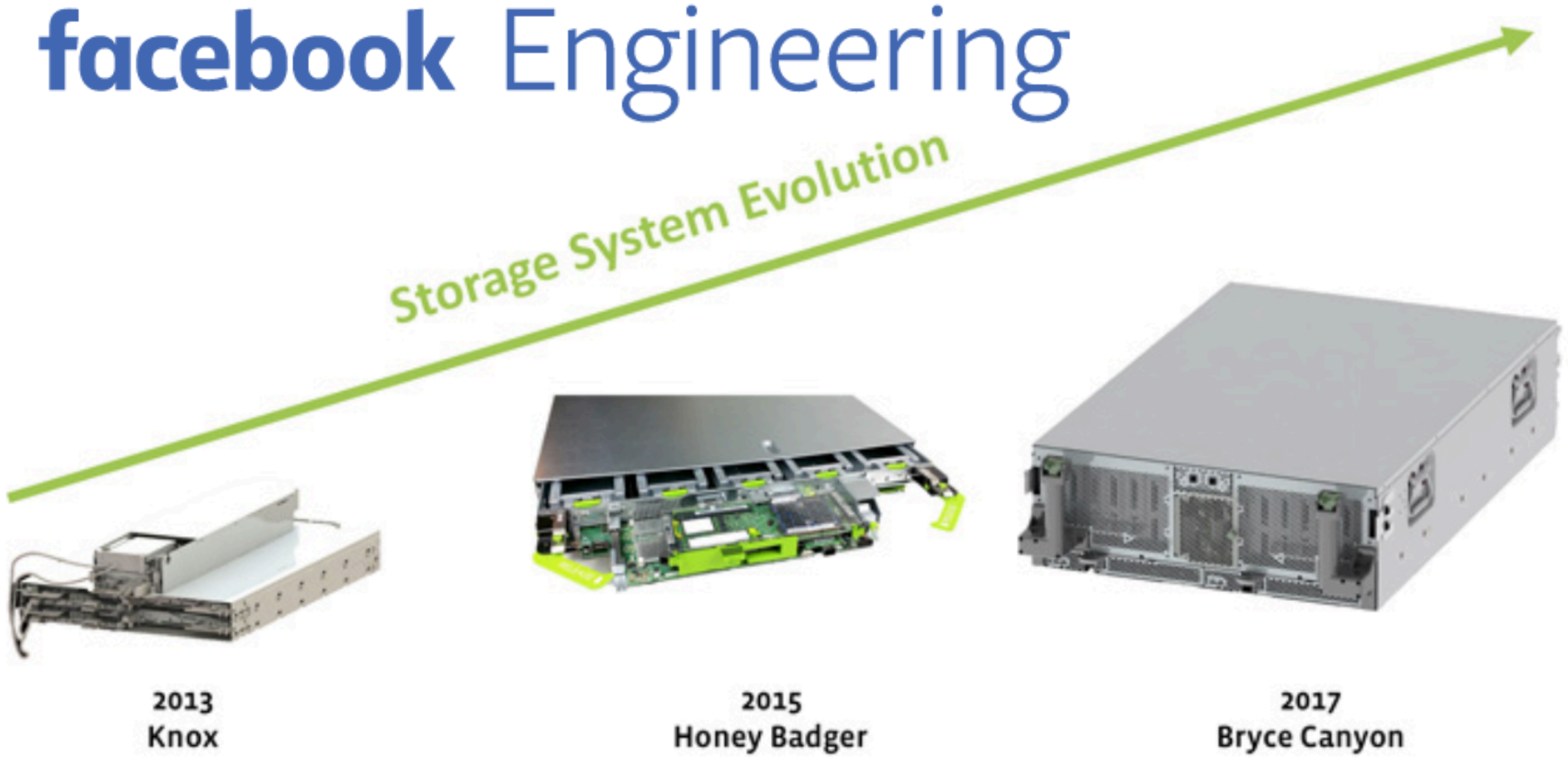
Separate compute and storage pools

- Manage and scale independently

A common practice in datacenters and clouds



facebook Engineering



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

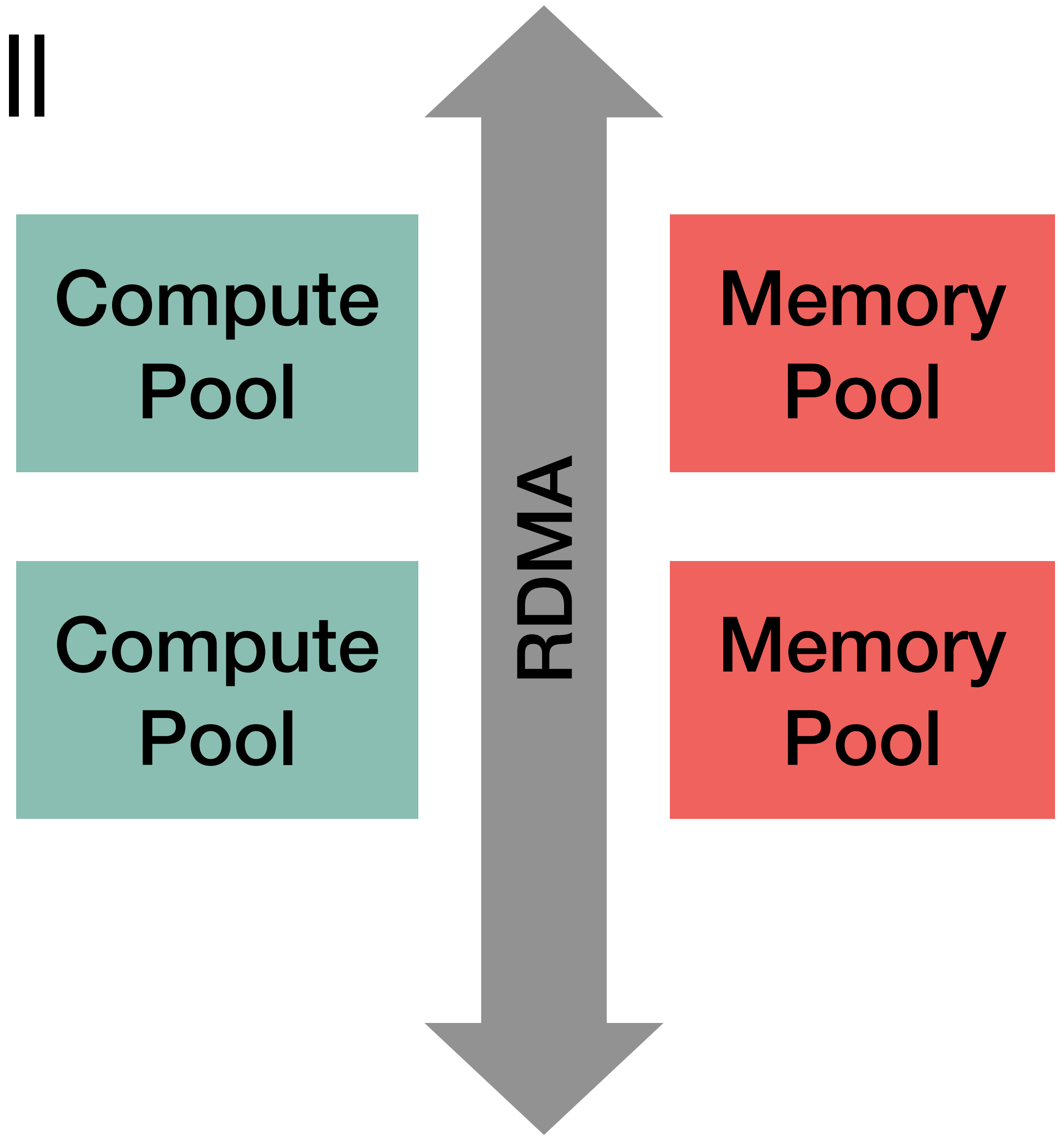
Yash Wate

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

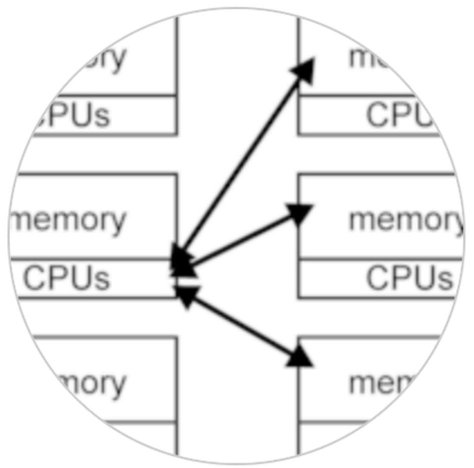


Microsoft

FaRM

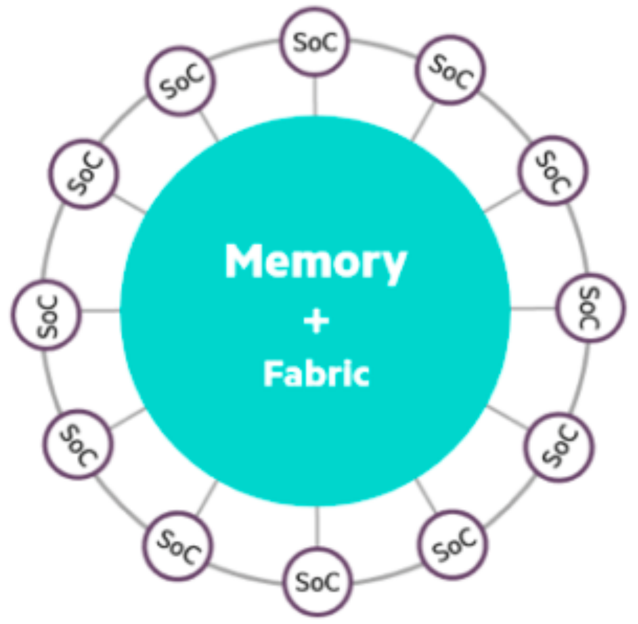
vmware

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?

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

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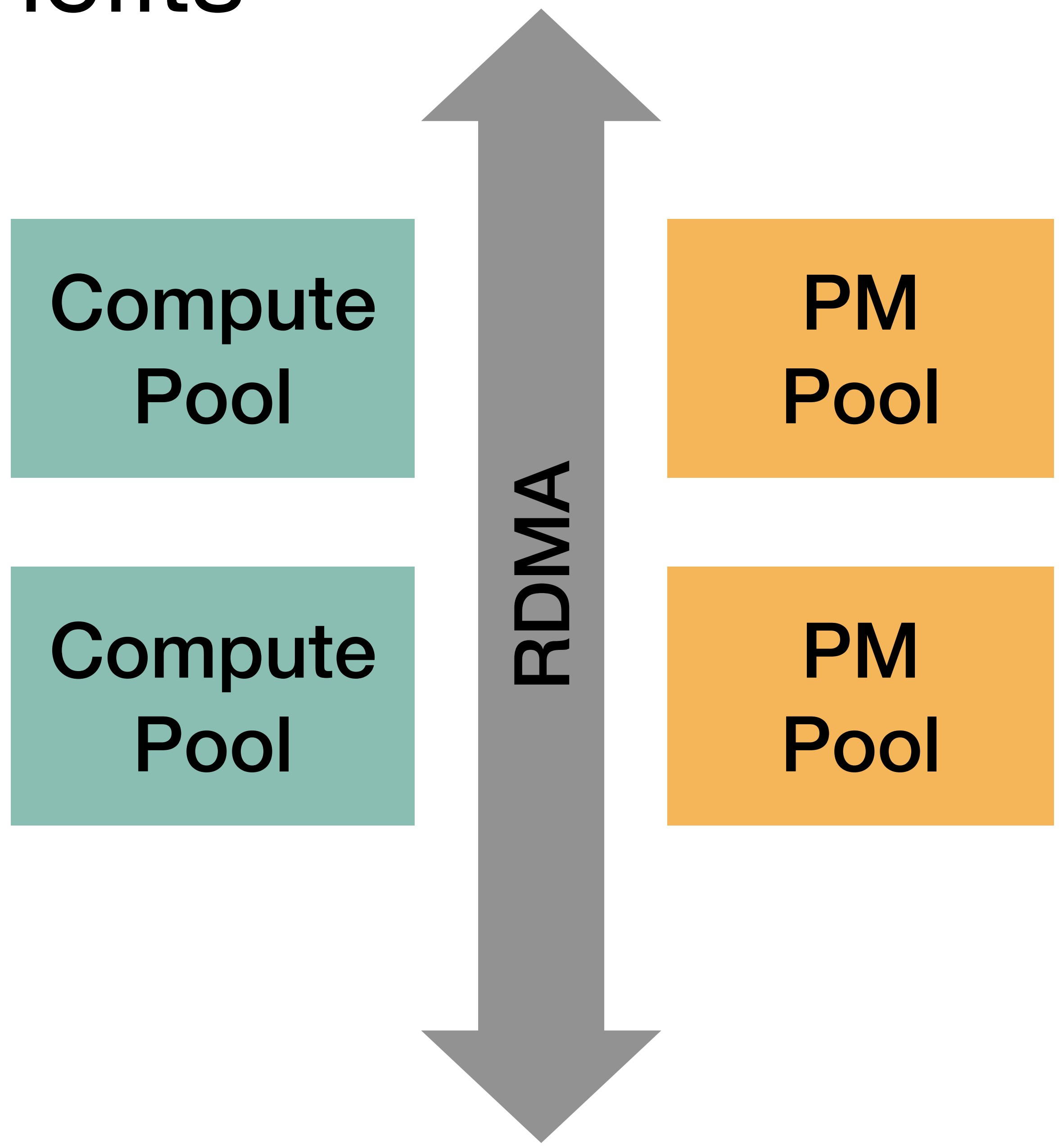
Disaggregating PM (DPM)

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



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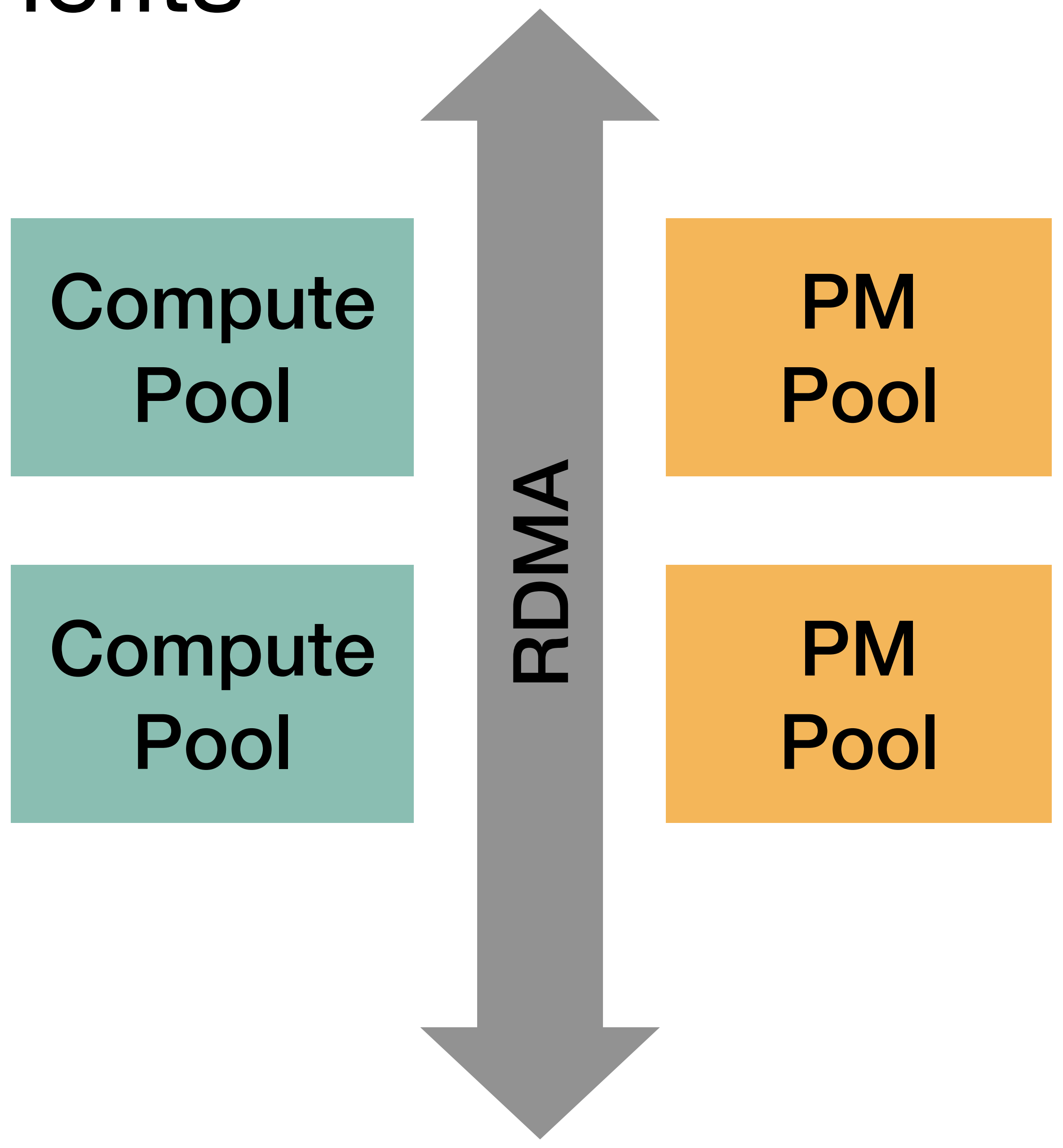
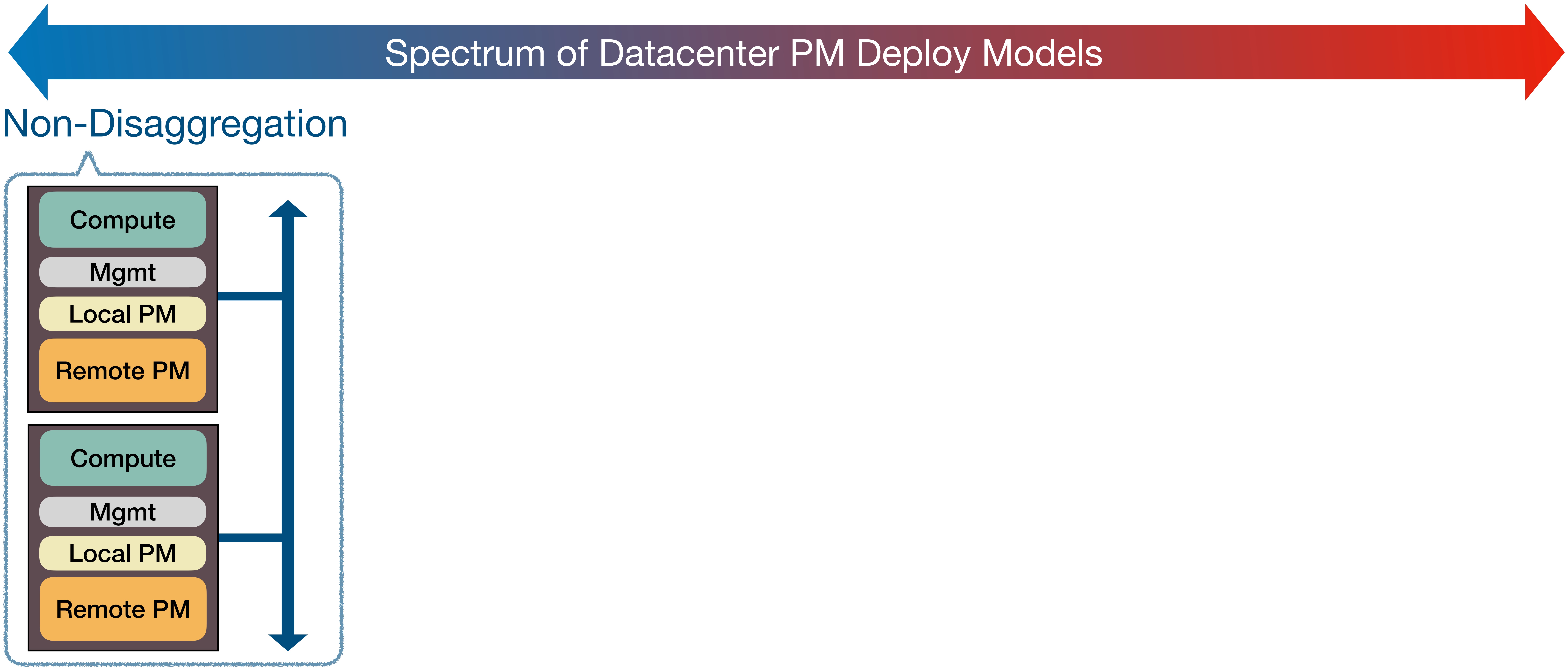
Use existing disaggregated systems for DPM?

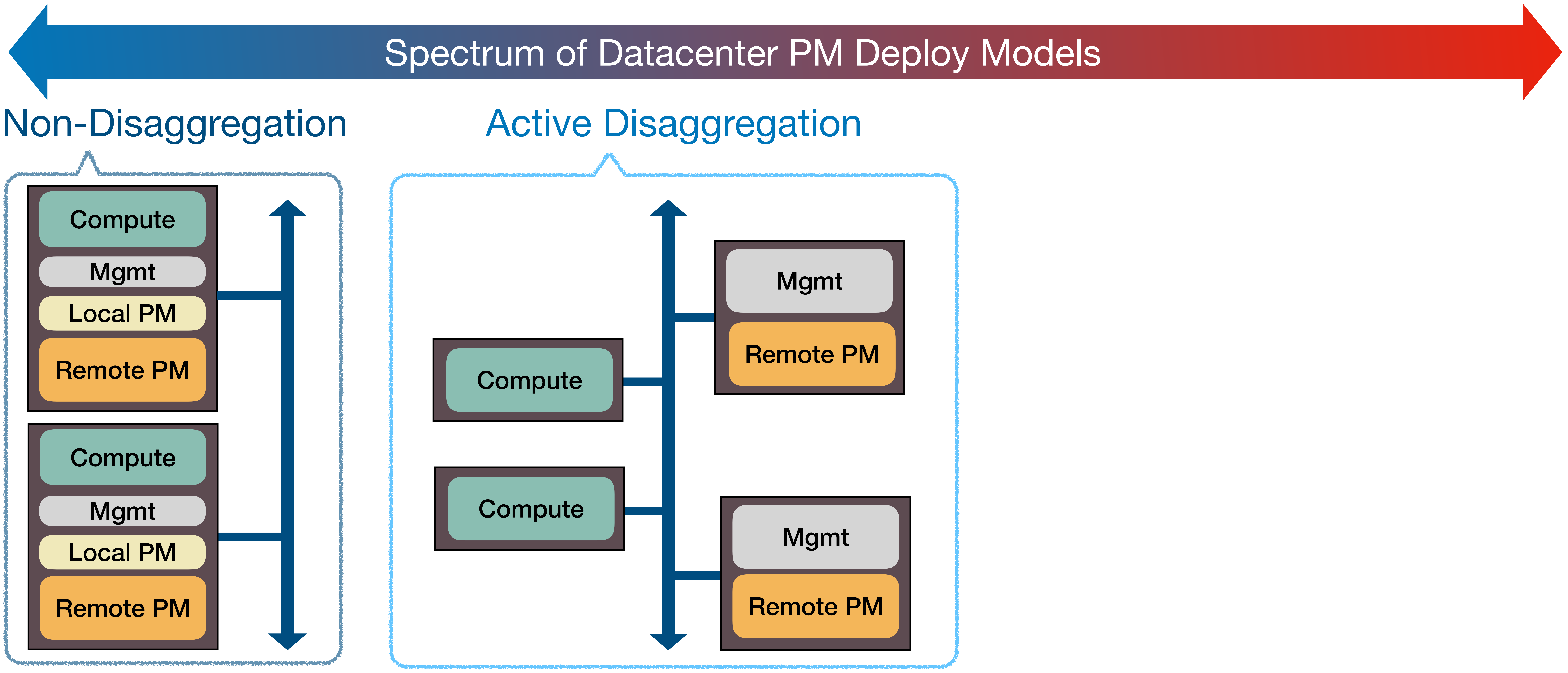
- Disaggregated storage: software stack too slow for fast PM
- Disaggregated memory: do not provide data reliability



Spectrum of Datacenter PM Deploy Models



Hotpot, SoCC’17
Octopus, ATC’17
Remote Regions, ATC’18



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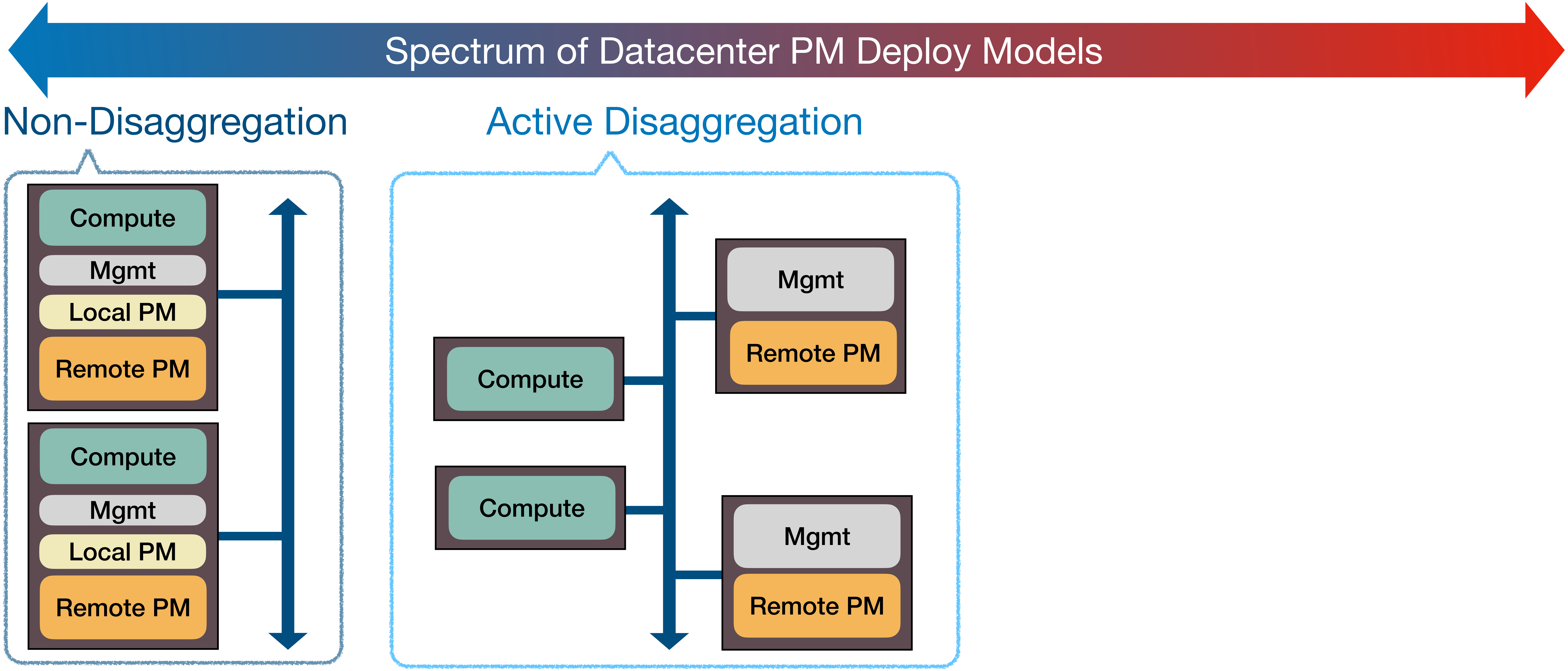
HyperLoop, SIGCOMM'18
Snowflake, NSDI'20

Traditional Storage Systems



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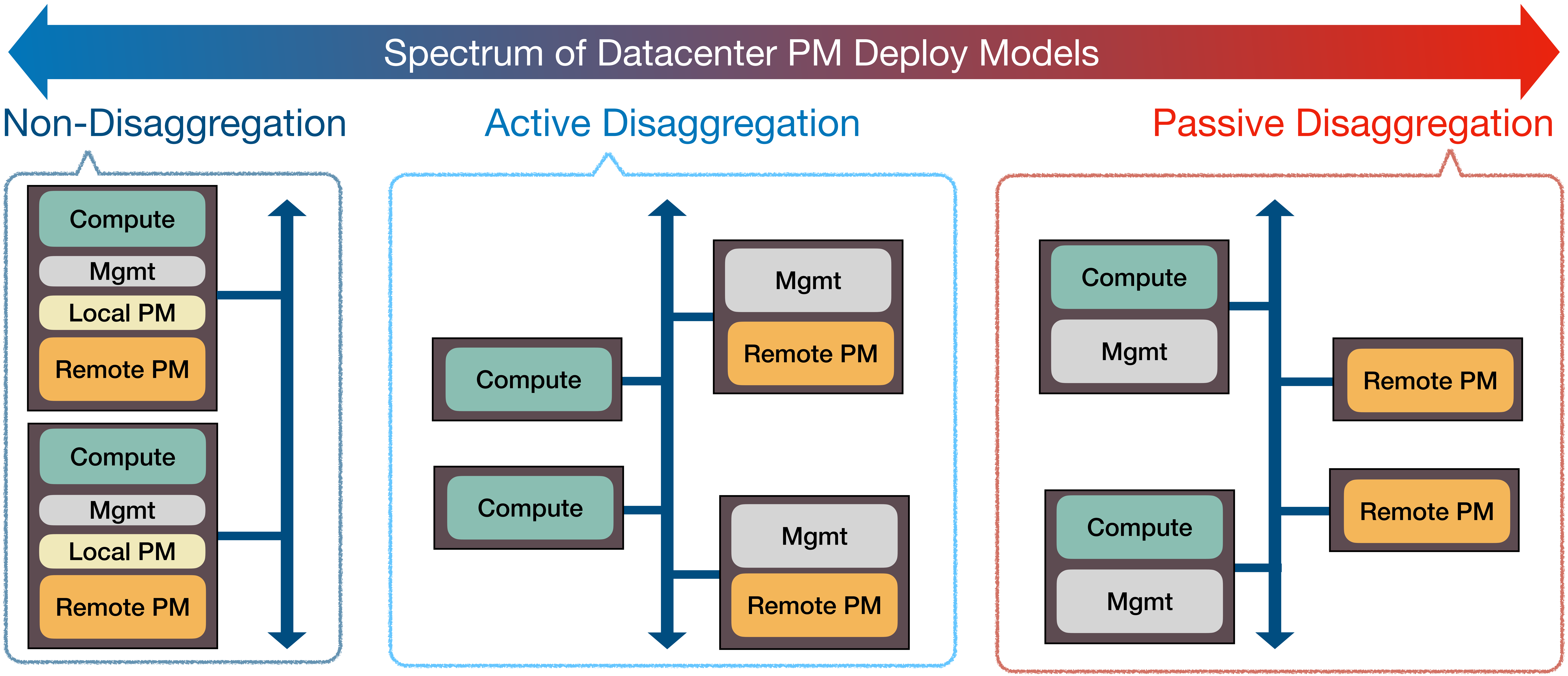
Unexplored Area!



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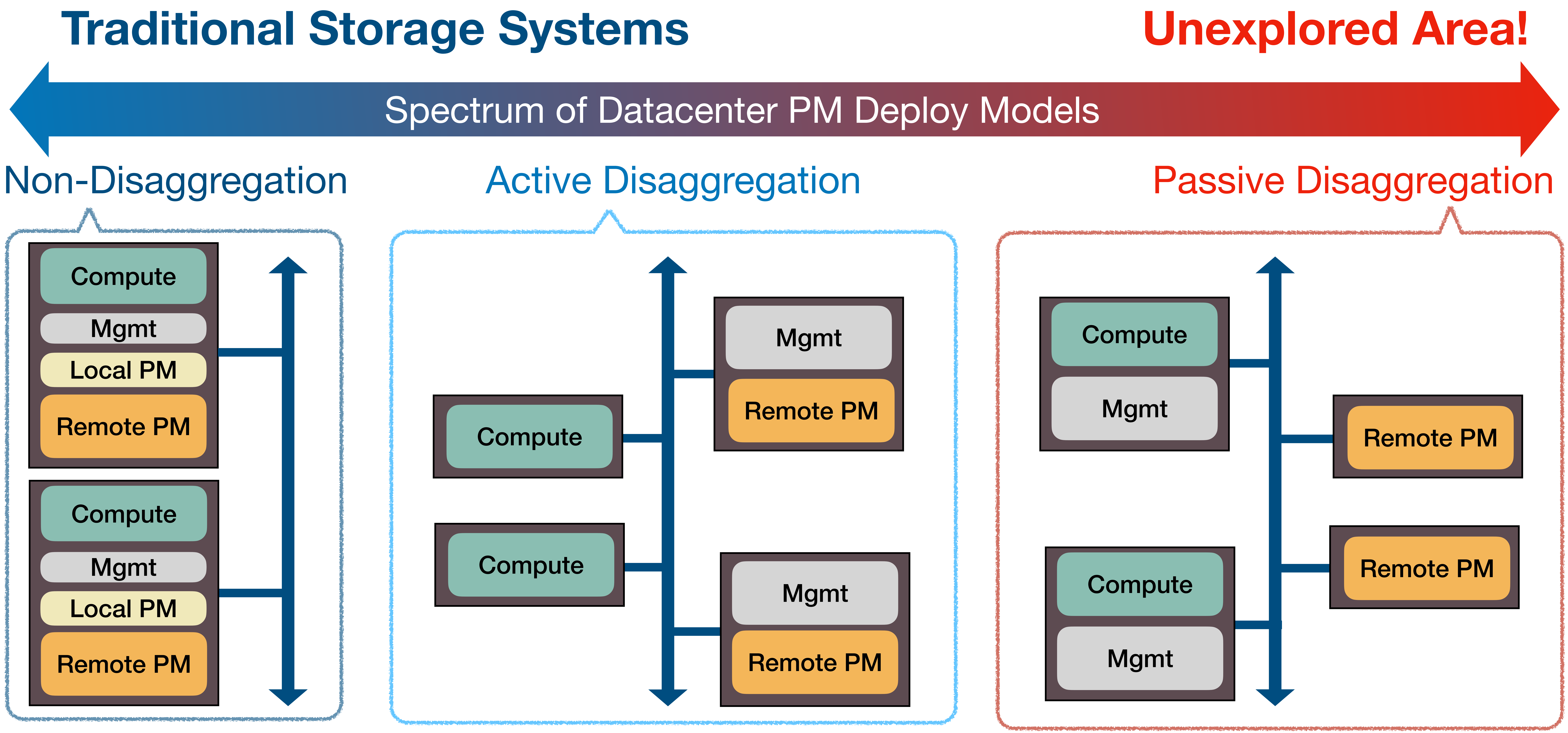
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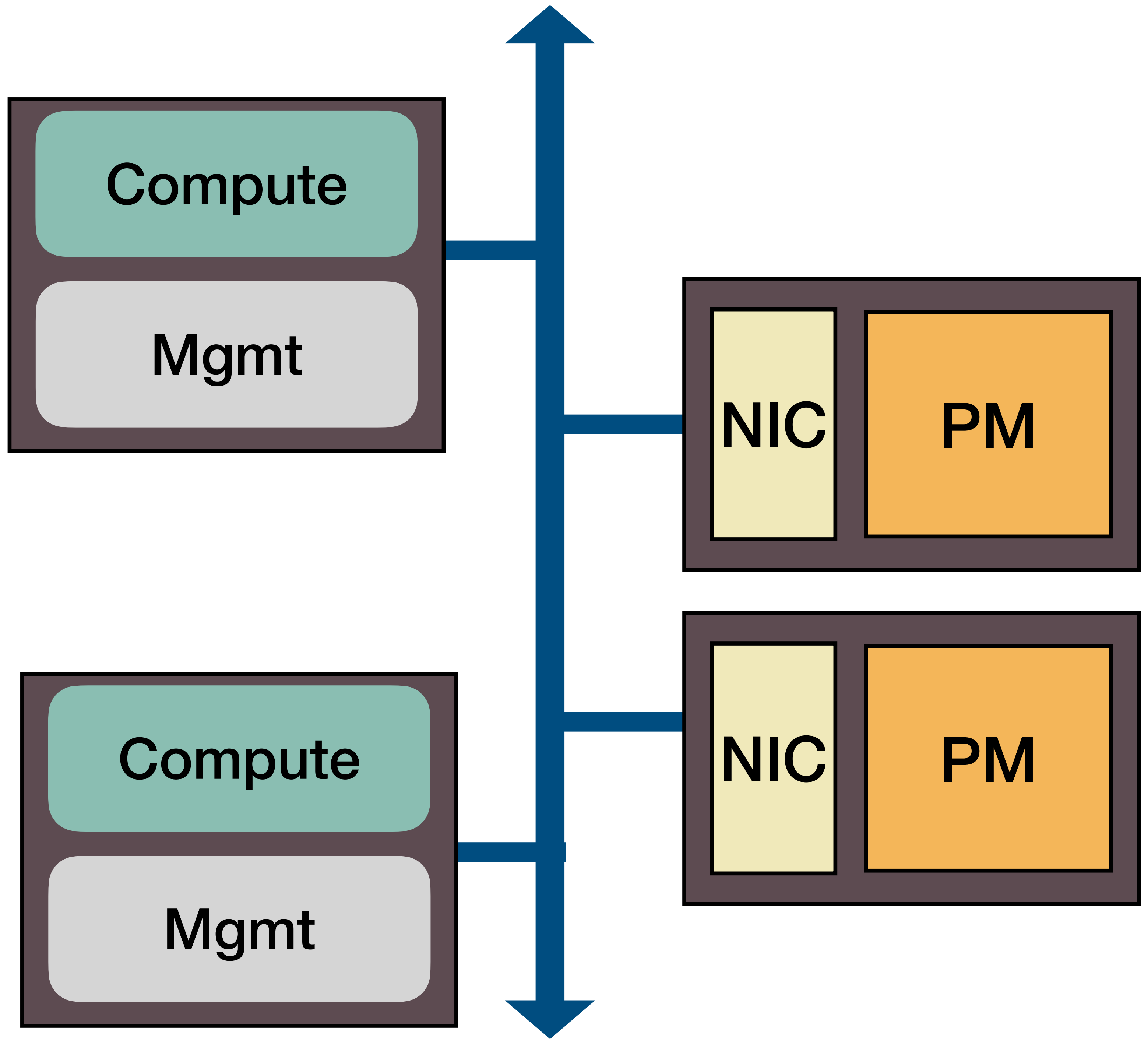
Passive Disaggregated PM (pDPM)



pDPM

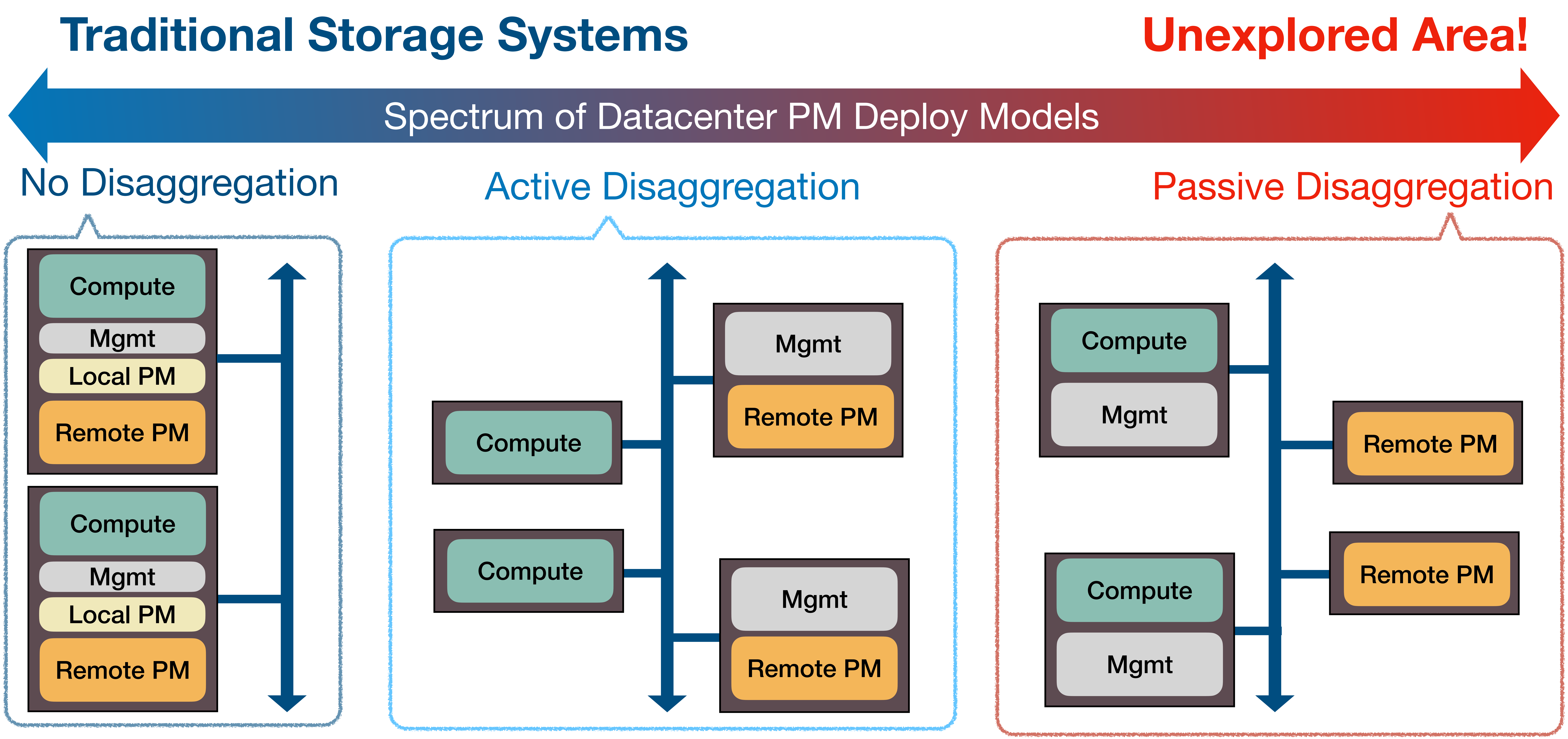
- Passive PM devices with NIC and PM
- Accessible only via network

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?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Where to process and manage data?

Spectrum of Datacenter PM Deploy Models

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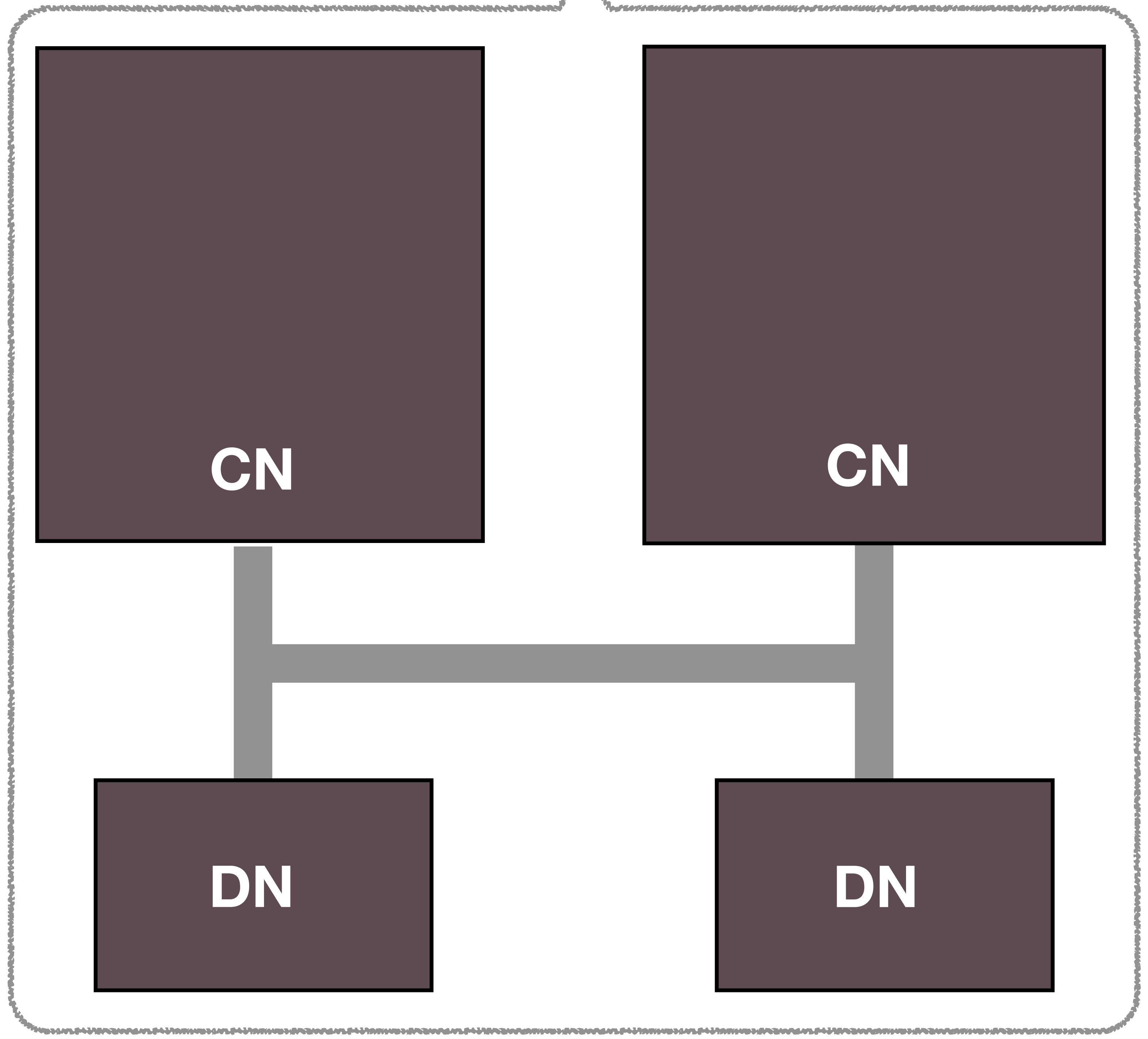
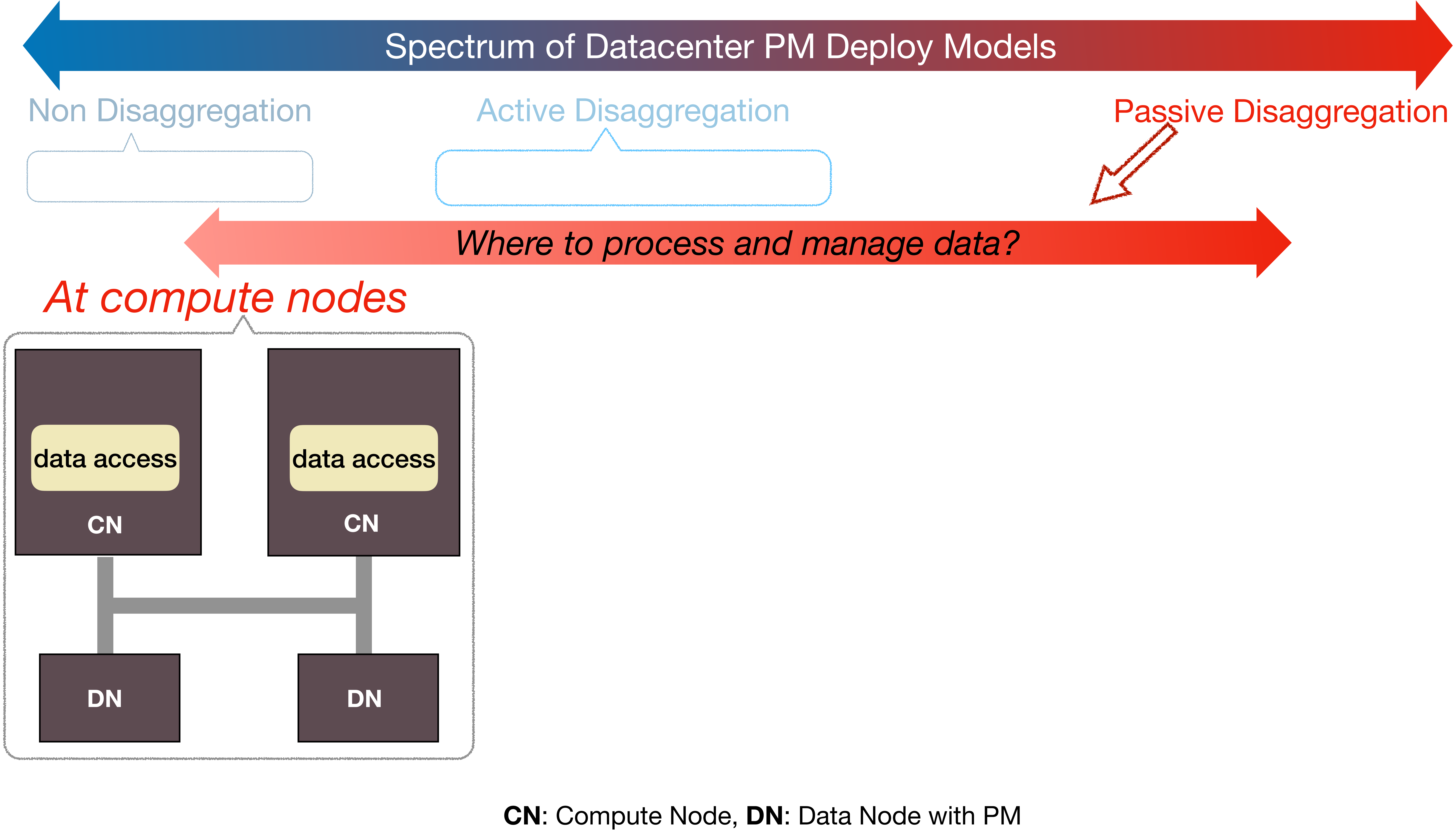
Where to process and manage data?

At compute nodes



CN: Compute Node, **DN**: Data Node with PM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Where to process and manage data?
At compute nodes
data access
CN
data access
CN
DN
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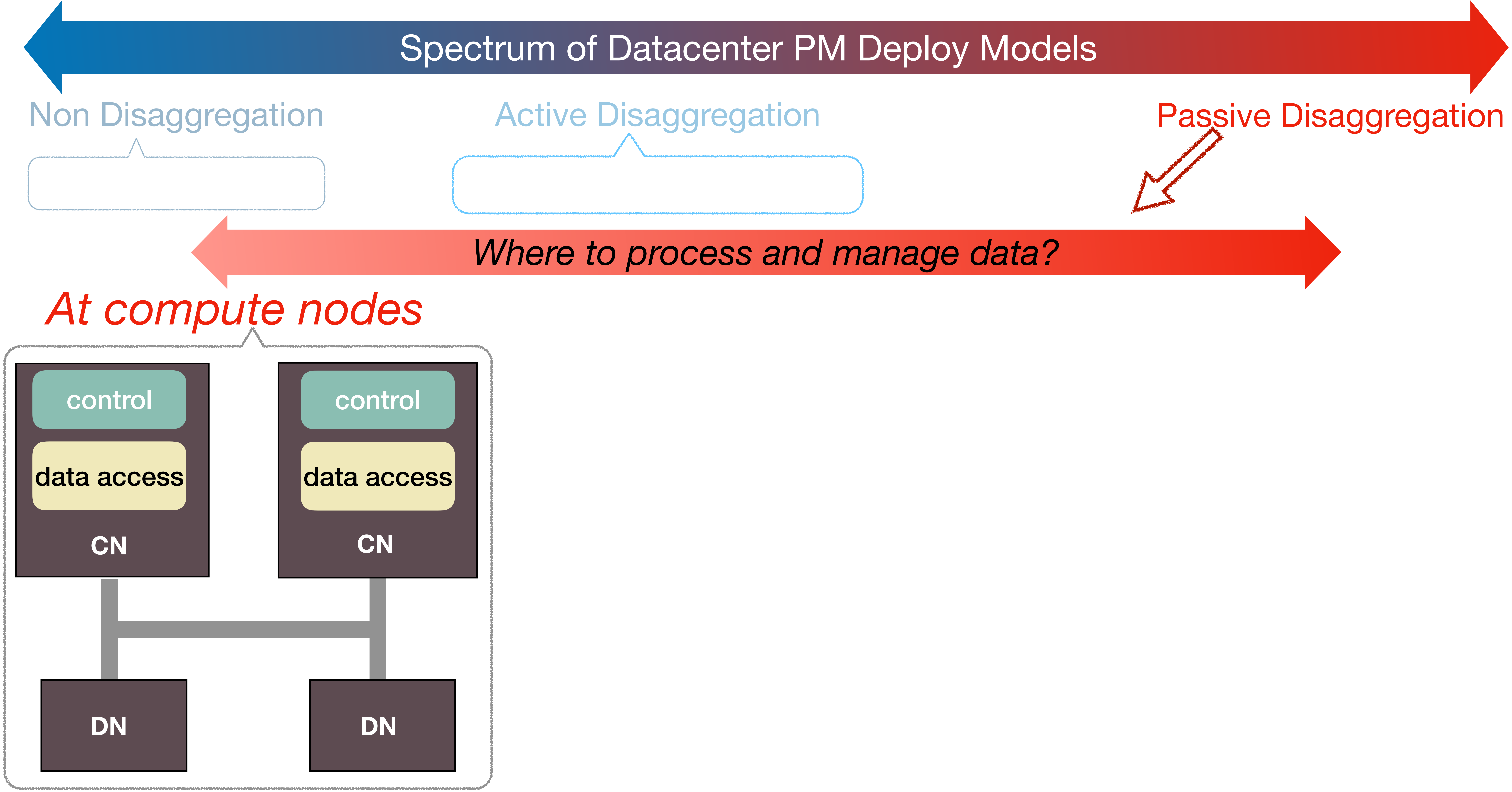

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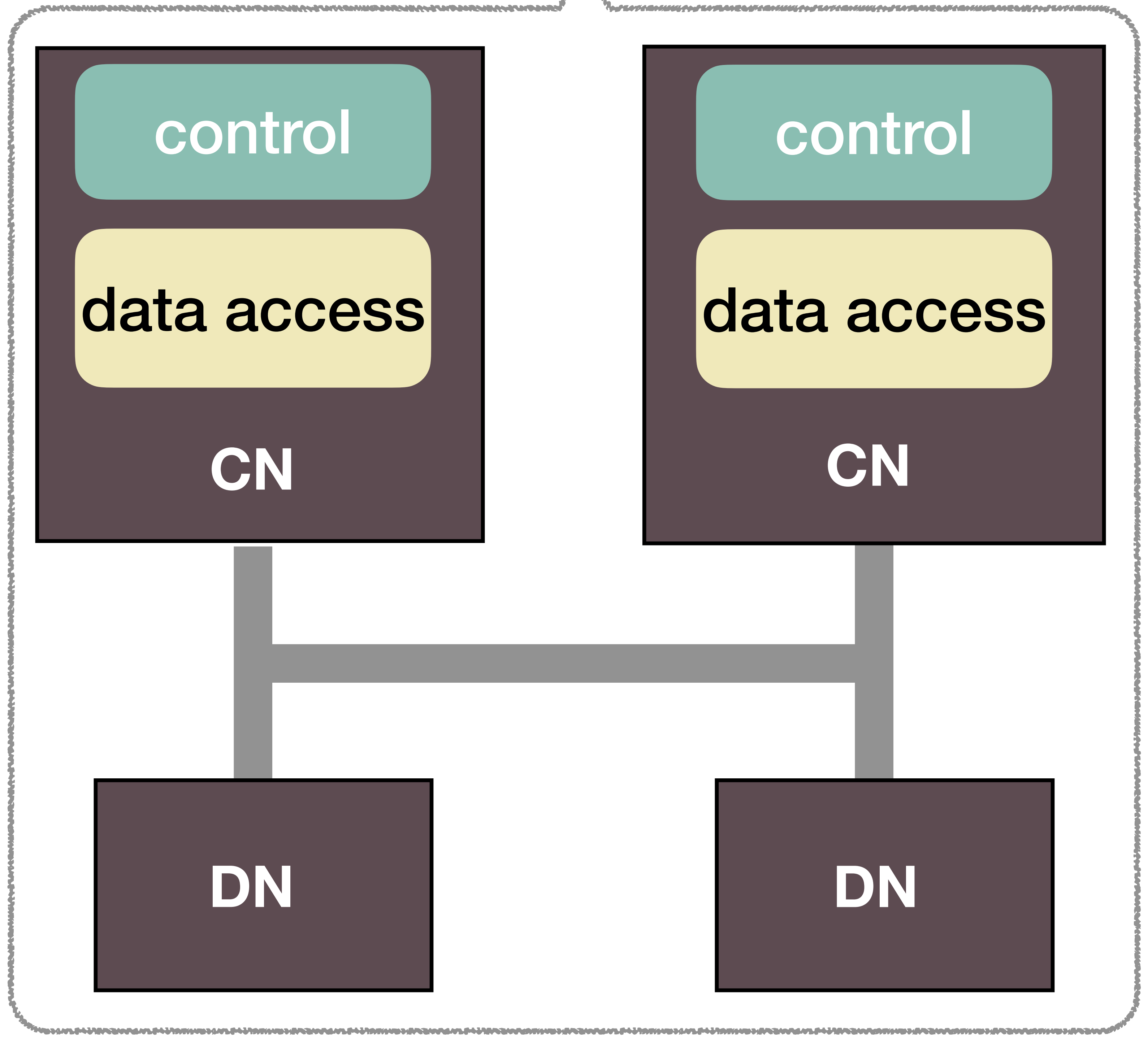
Spectrum of Datacenter PM Deploy Models

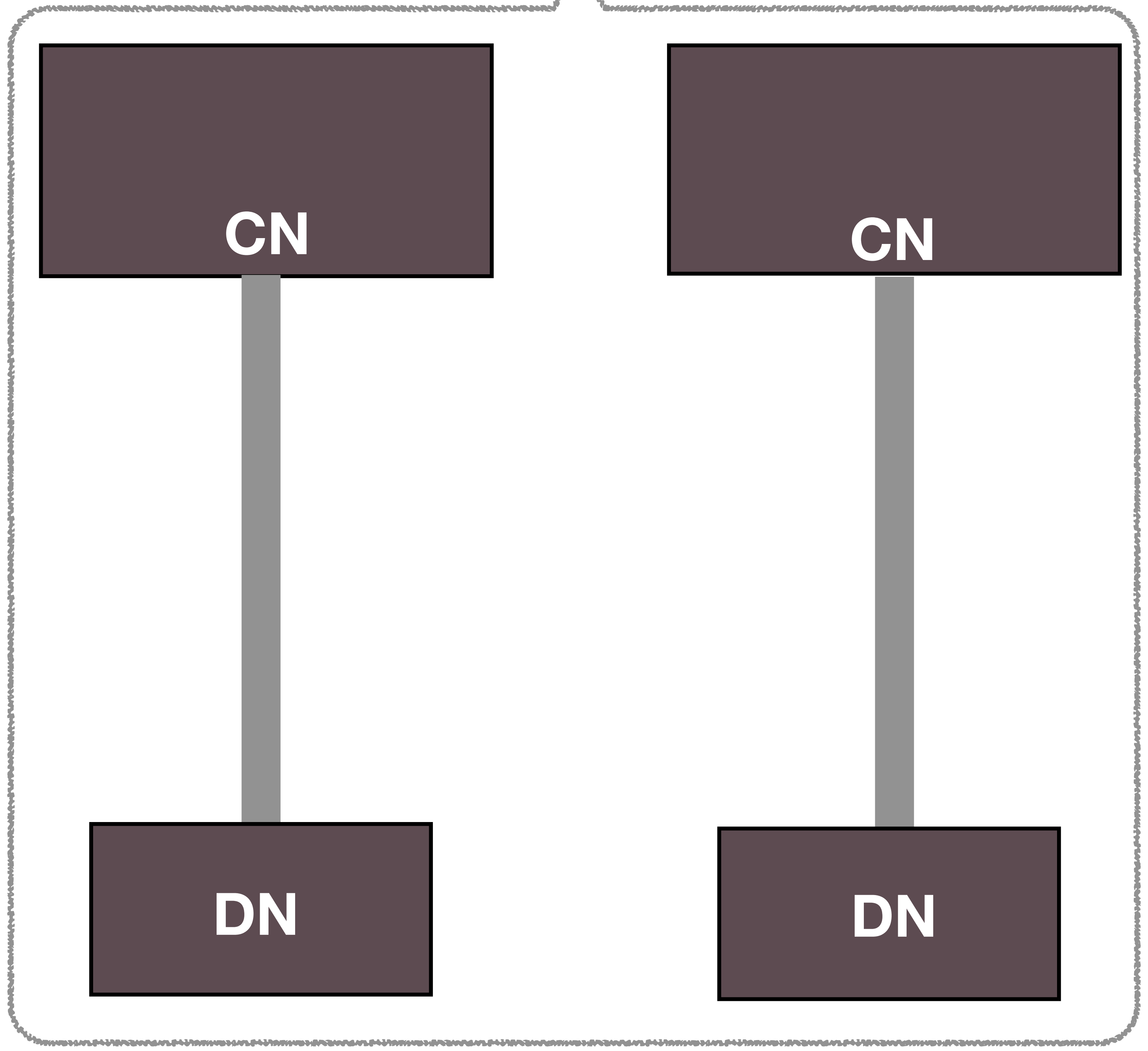
Non Disaggregation | Active Disaggregation | Passive Disaggregation

Where to process and manage data?

At compute nodes



At a coordinator



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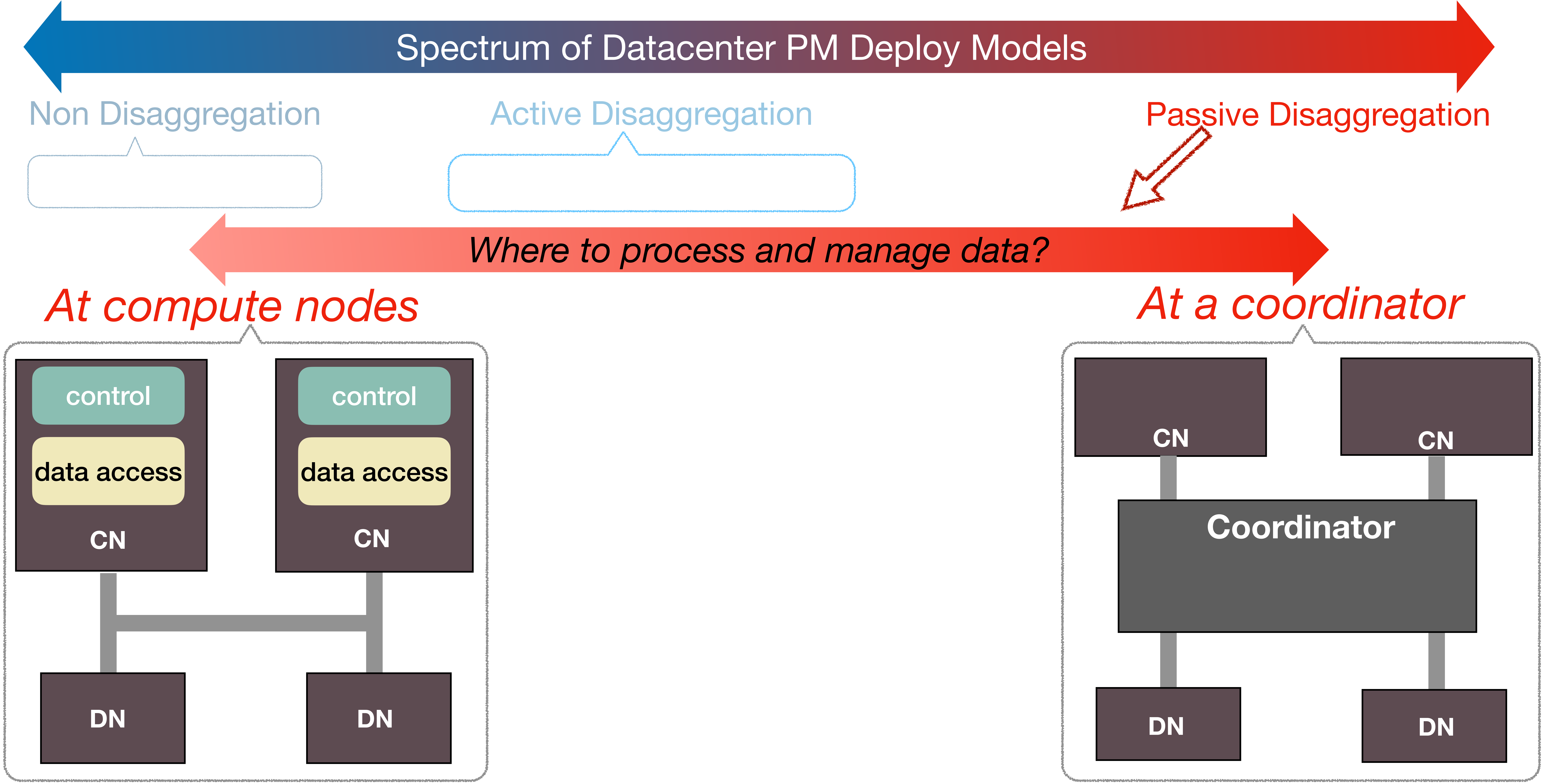

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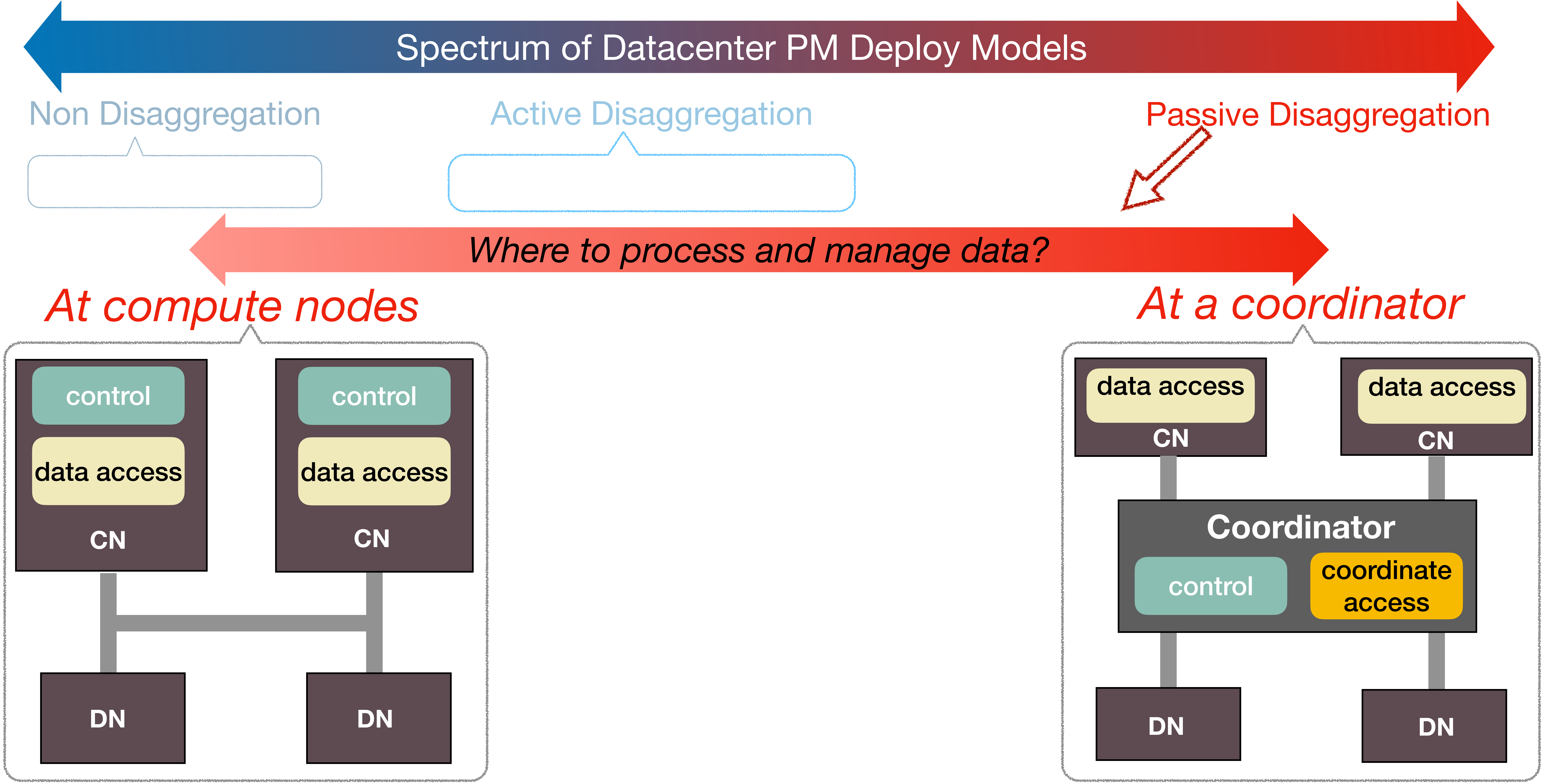

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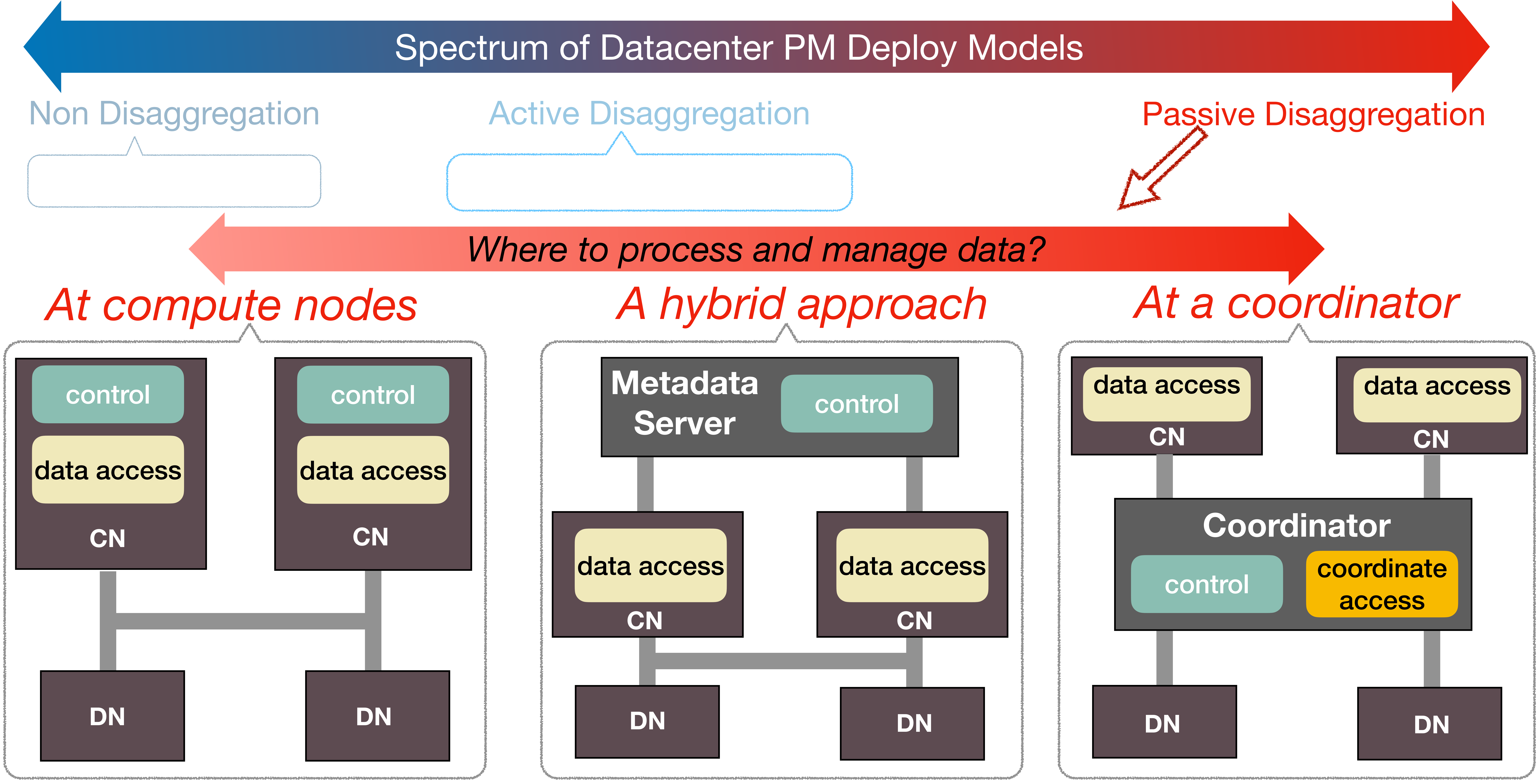

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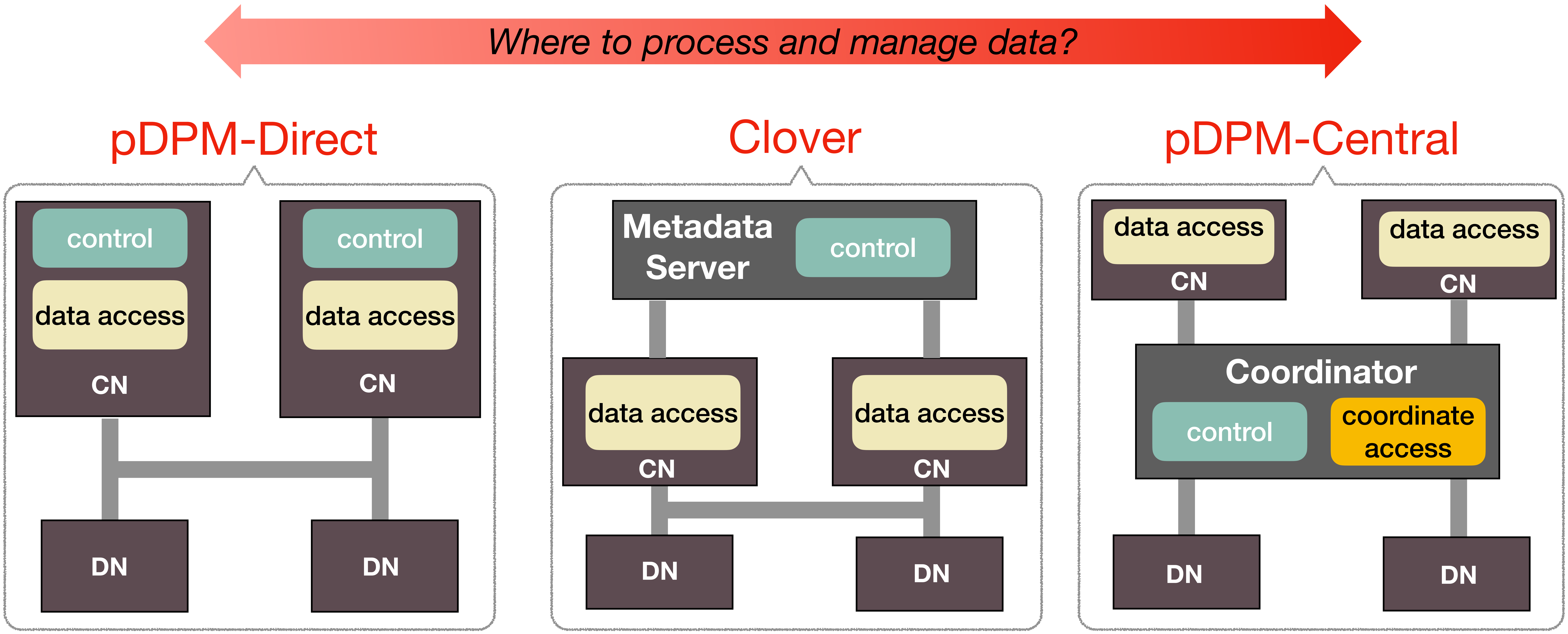
Passive Disaggregated PM (pDPM) Systems

- 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



Where to process and manage data?
pDPM-Direct
control
data access
CN
control
data access
CN
DN
DN
Clover
Metadata Server
control
data access
CN
data access
CN
DN
DN
pDPM-Central
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data access
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Coordinator
control
coordinate access
DN
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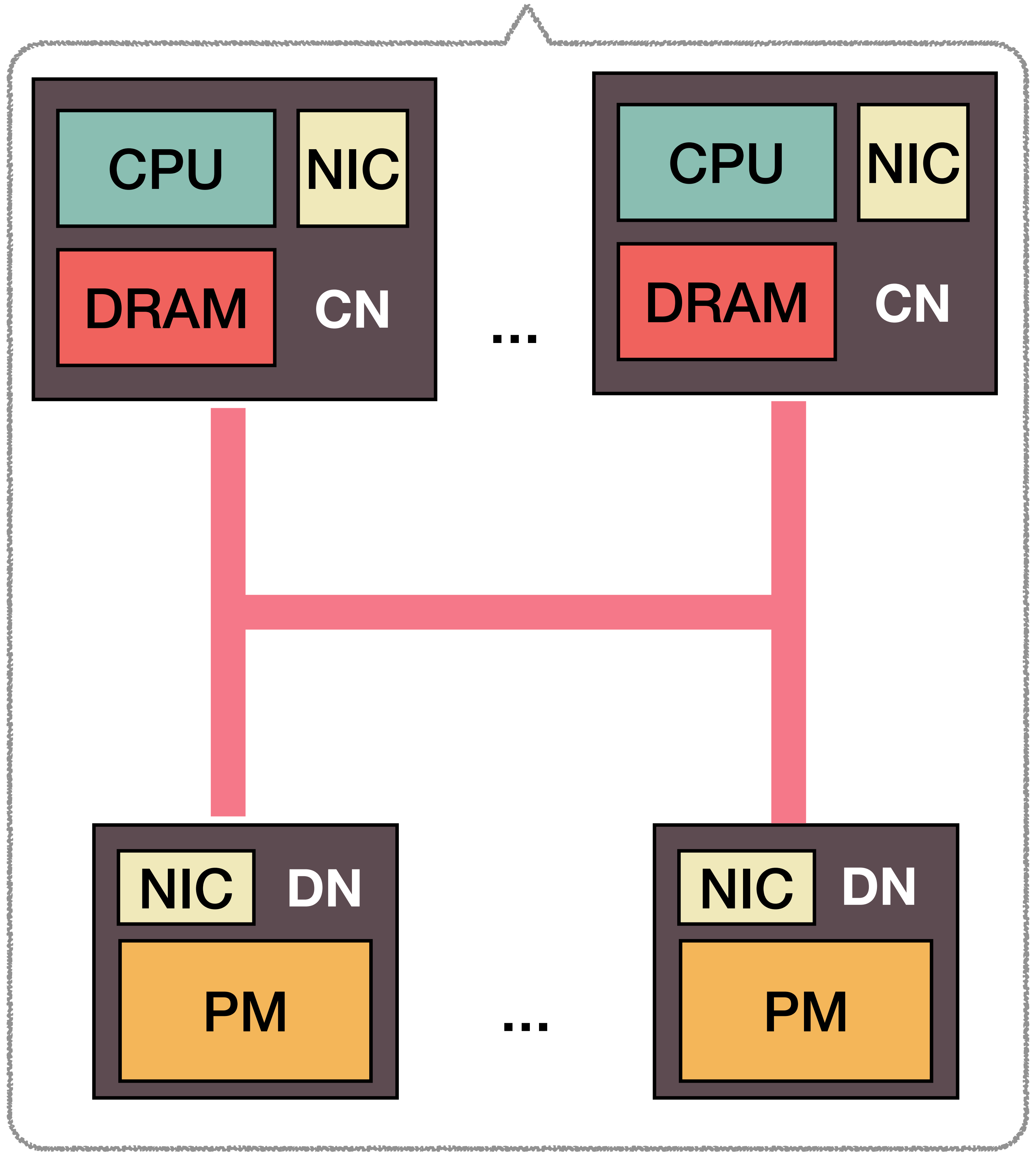
pDPM-Direct: Directly Access and Manage DNs from CNs



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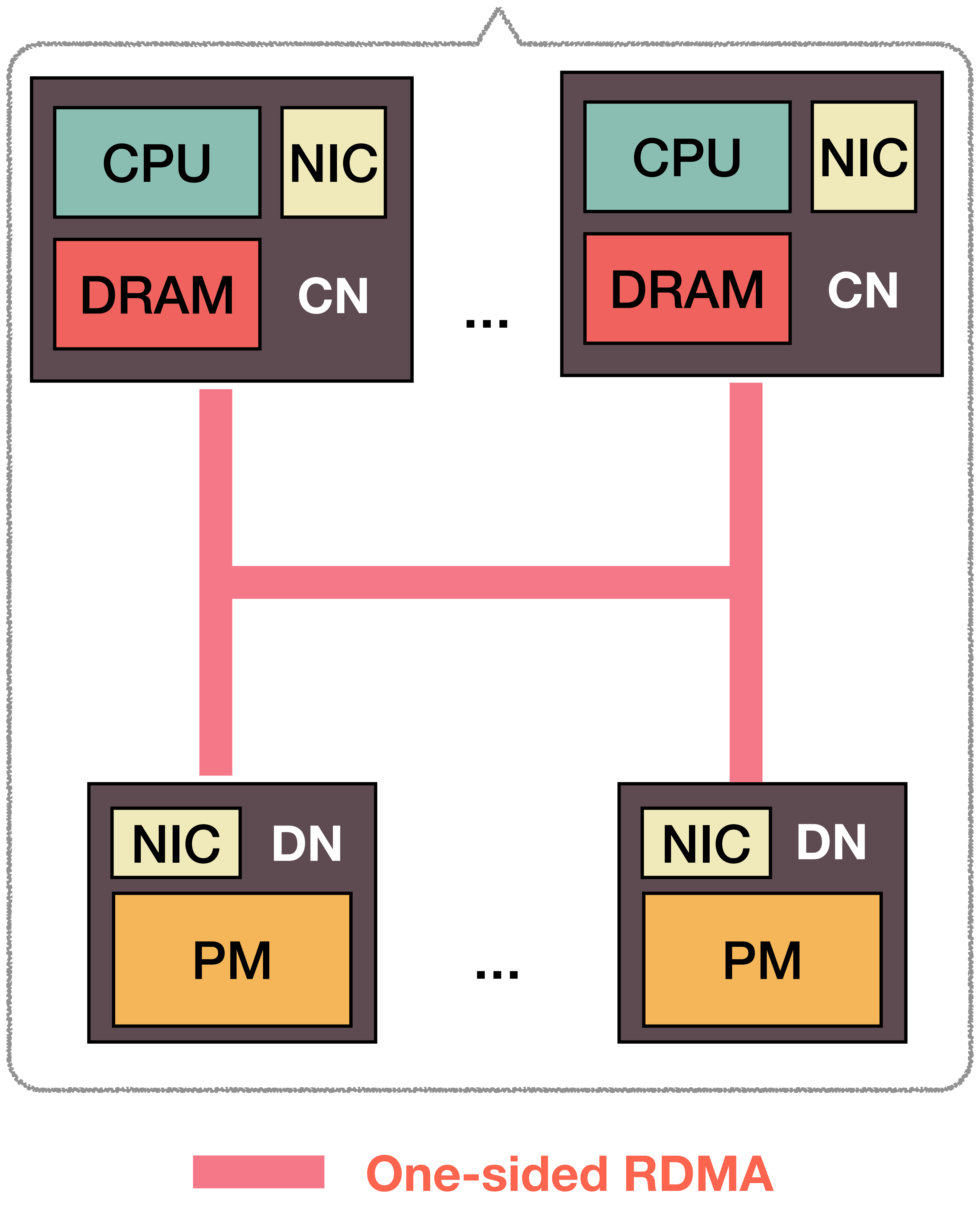

Overall Architecture

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

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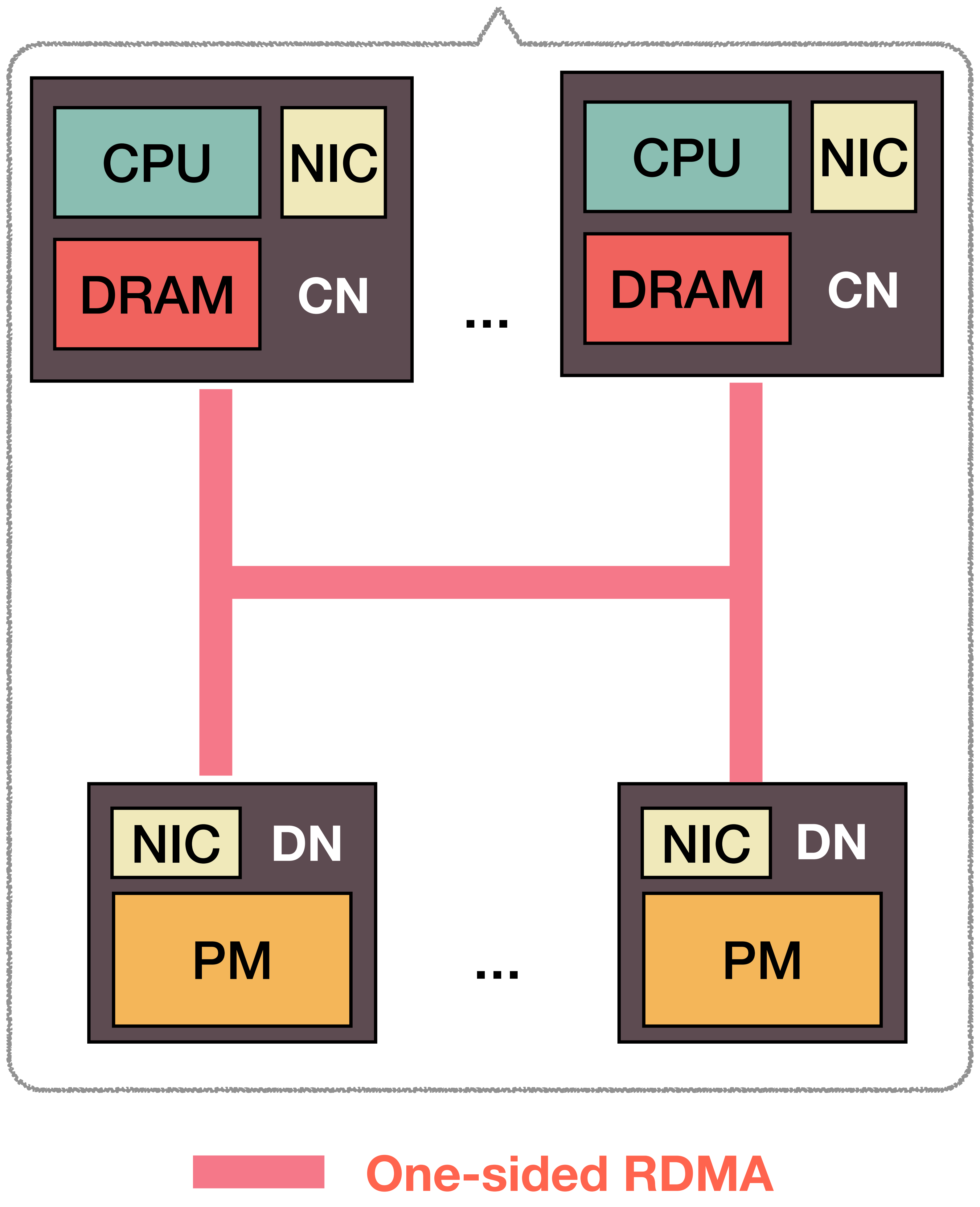

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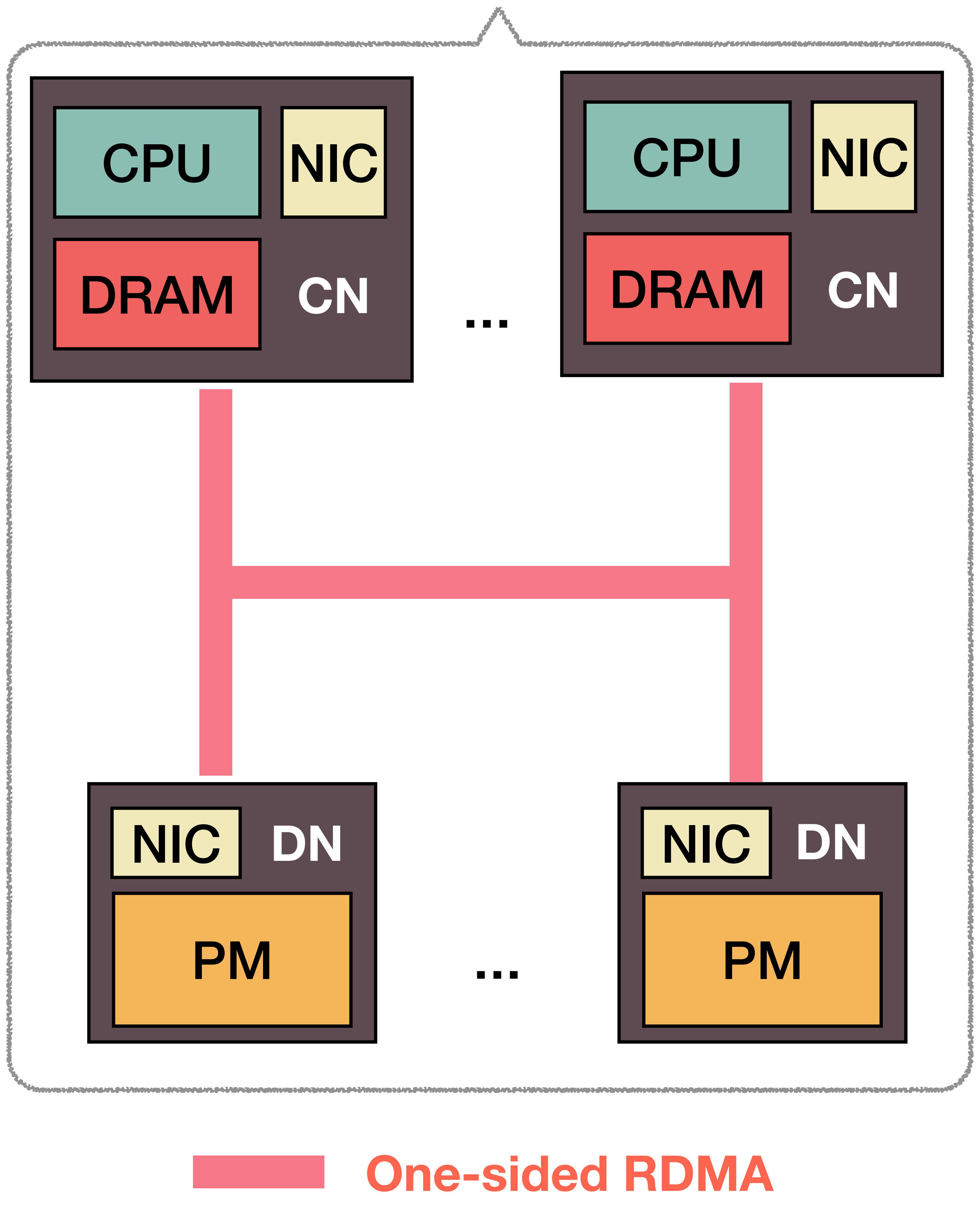

Overall Architecture

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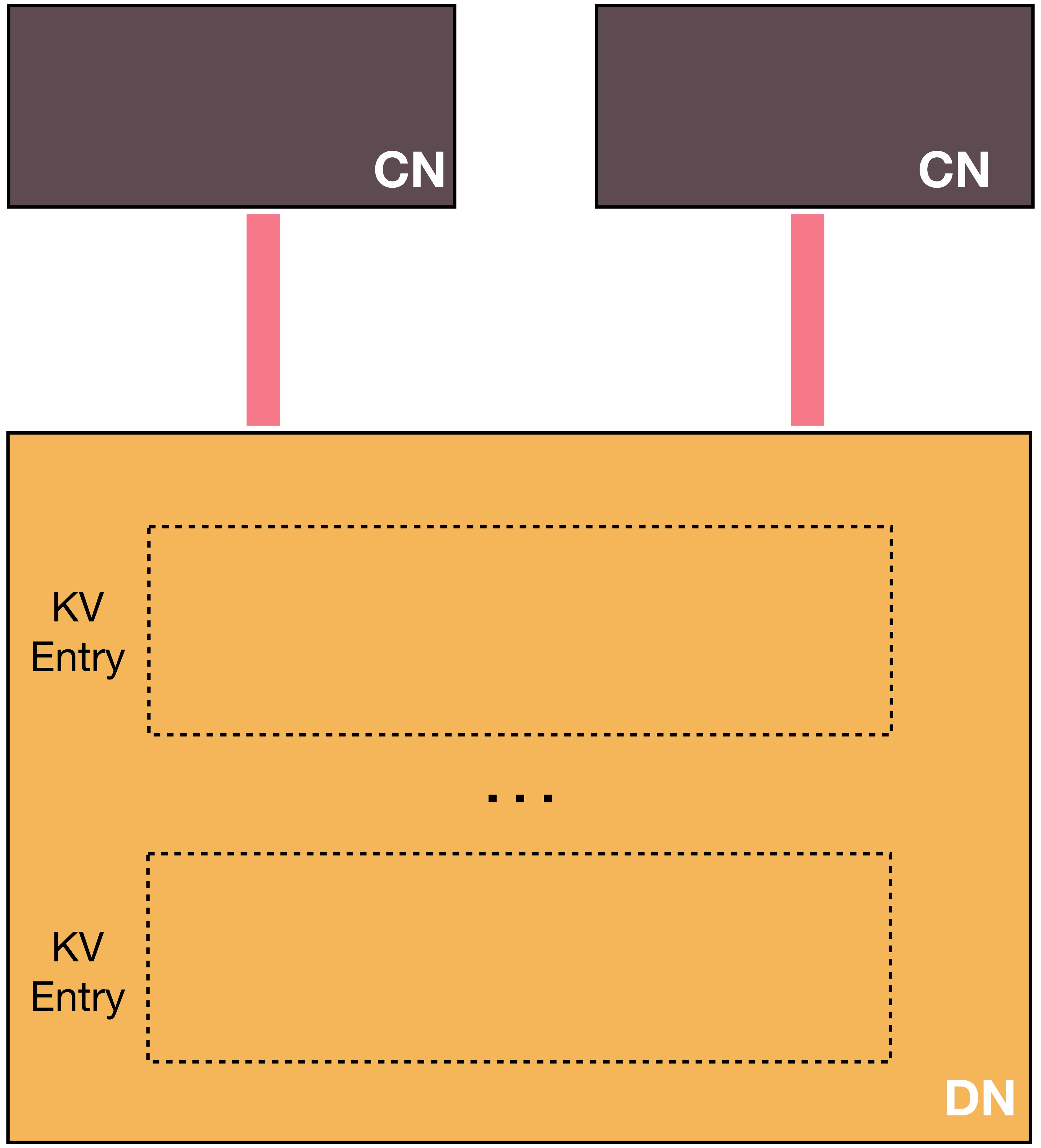
Challenges

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

Our solution

pDPM-Direct



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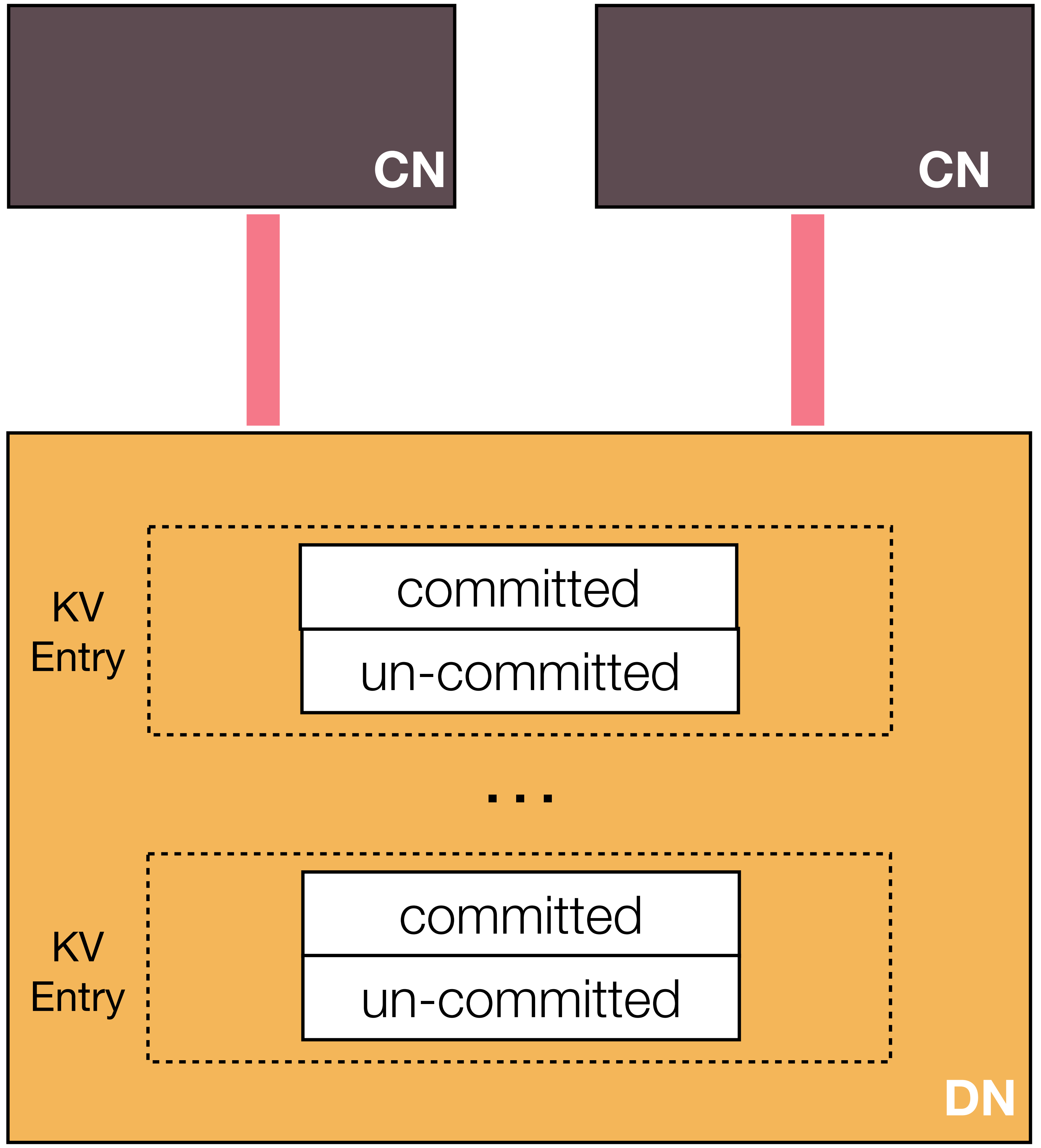

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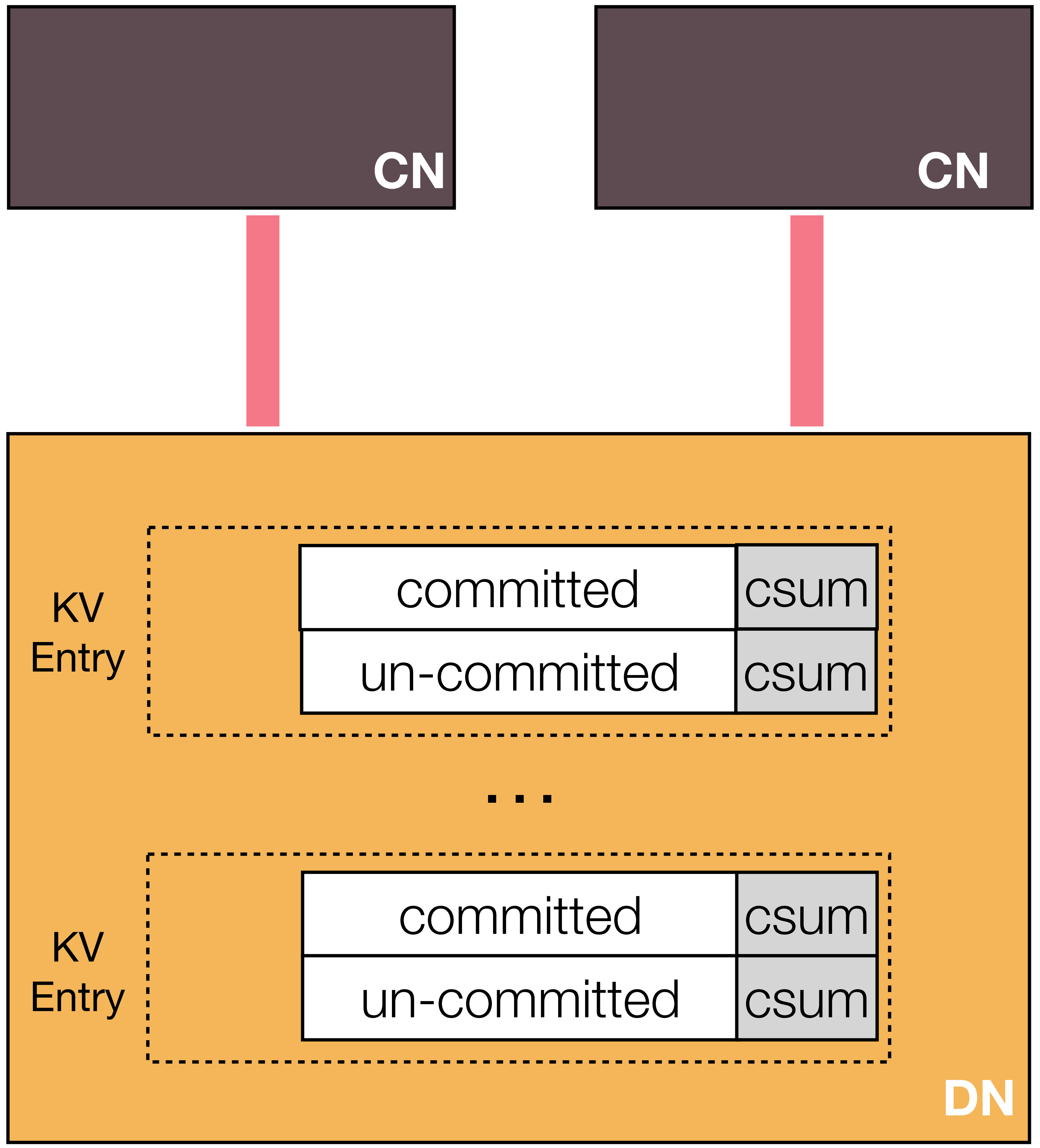

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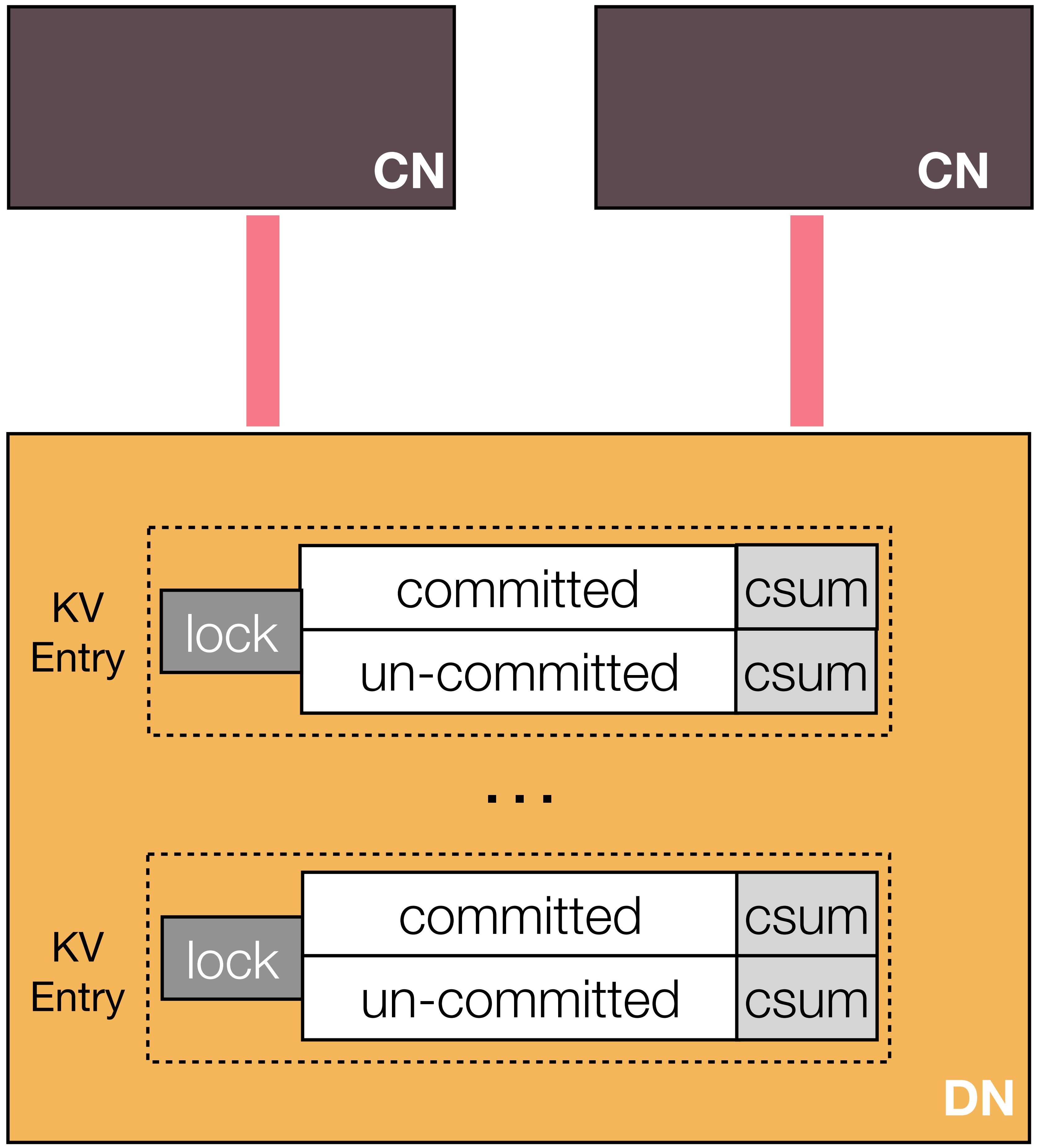

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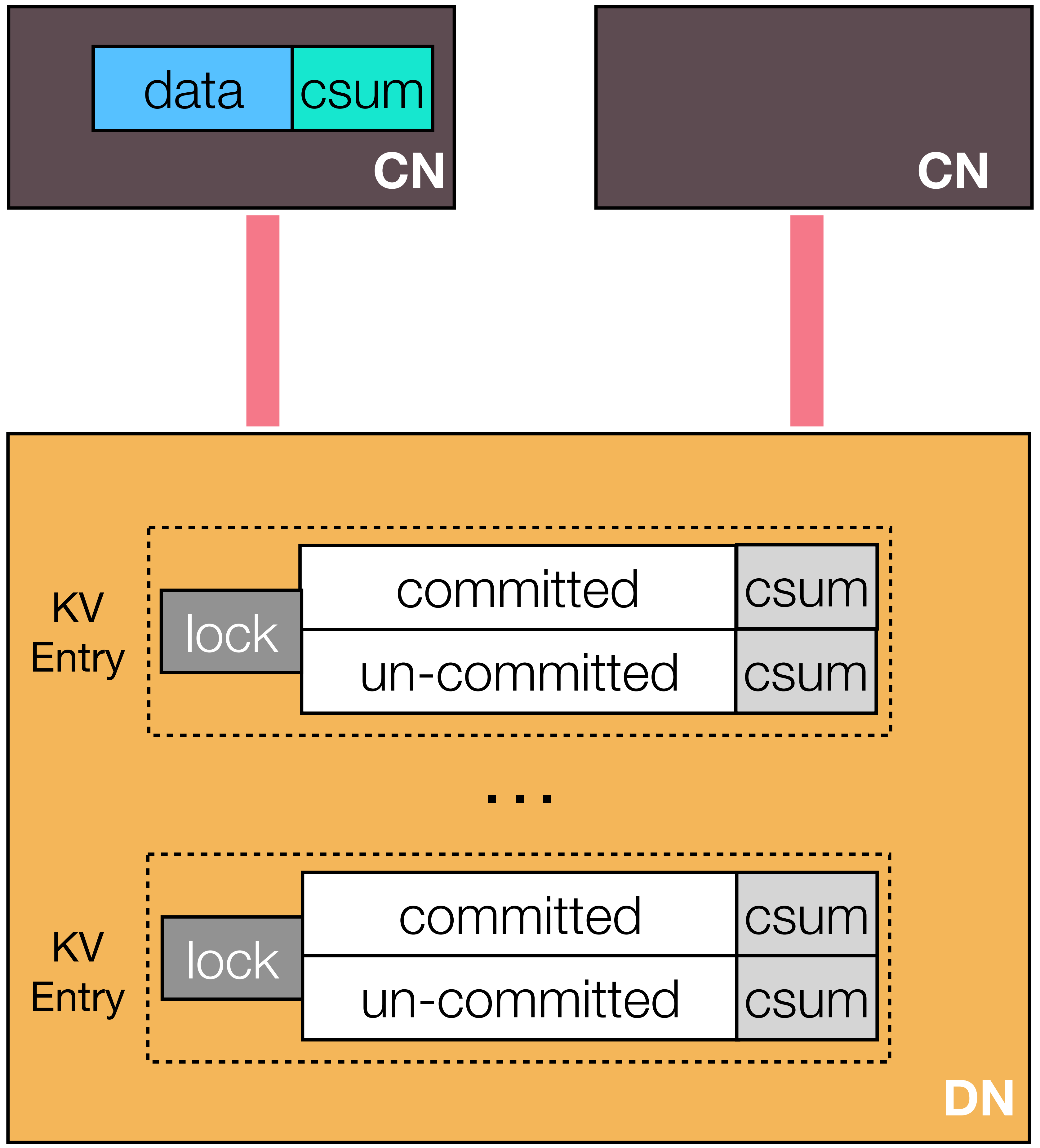

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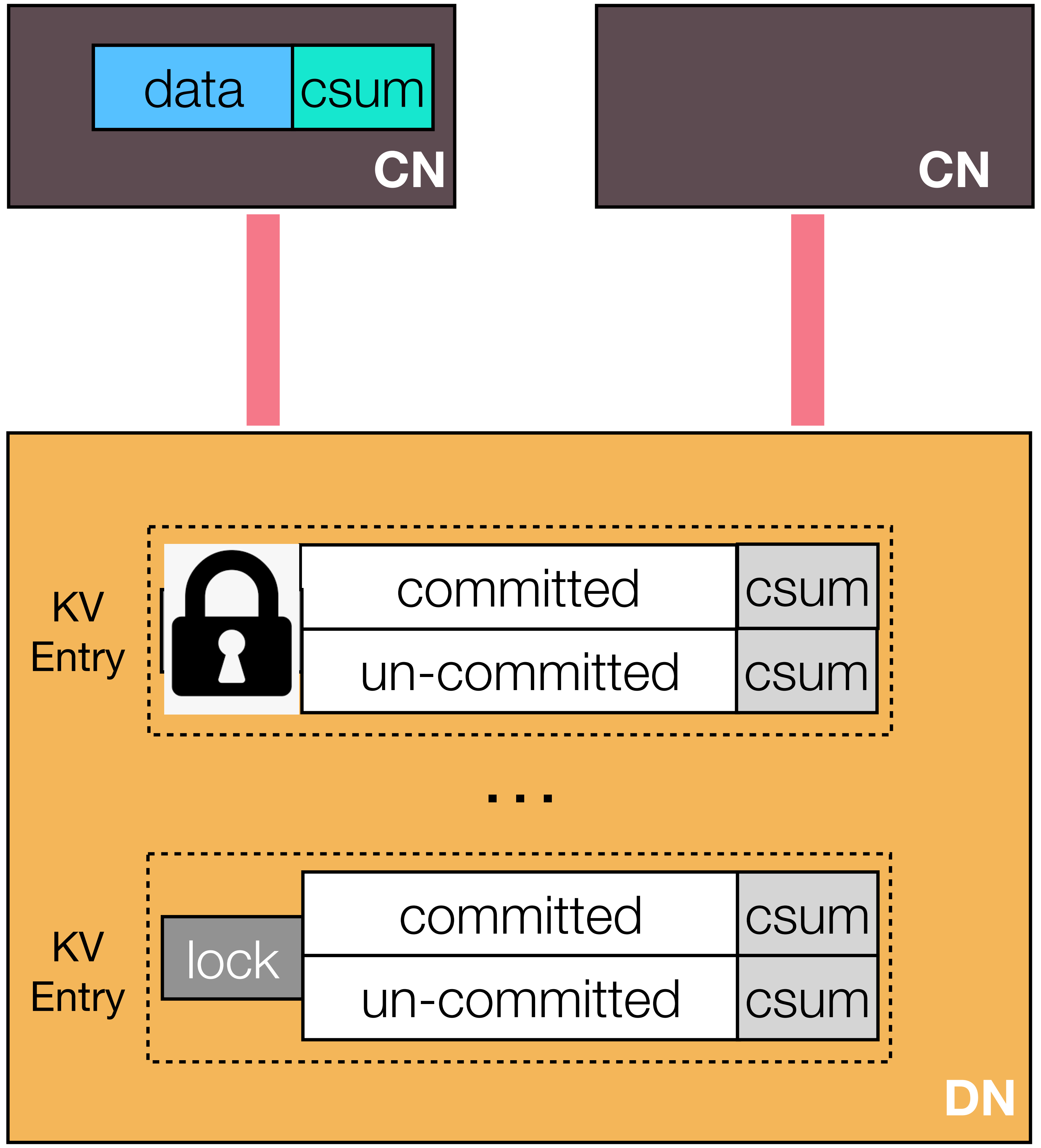

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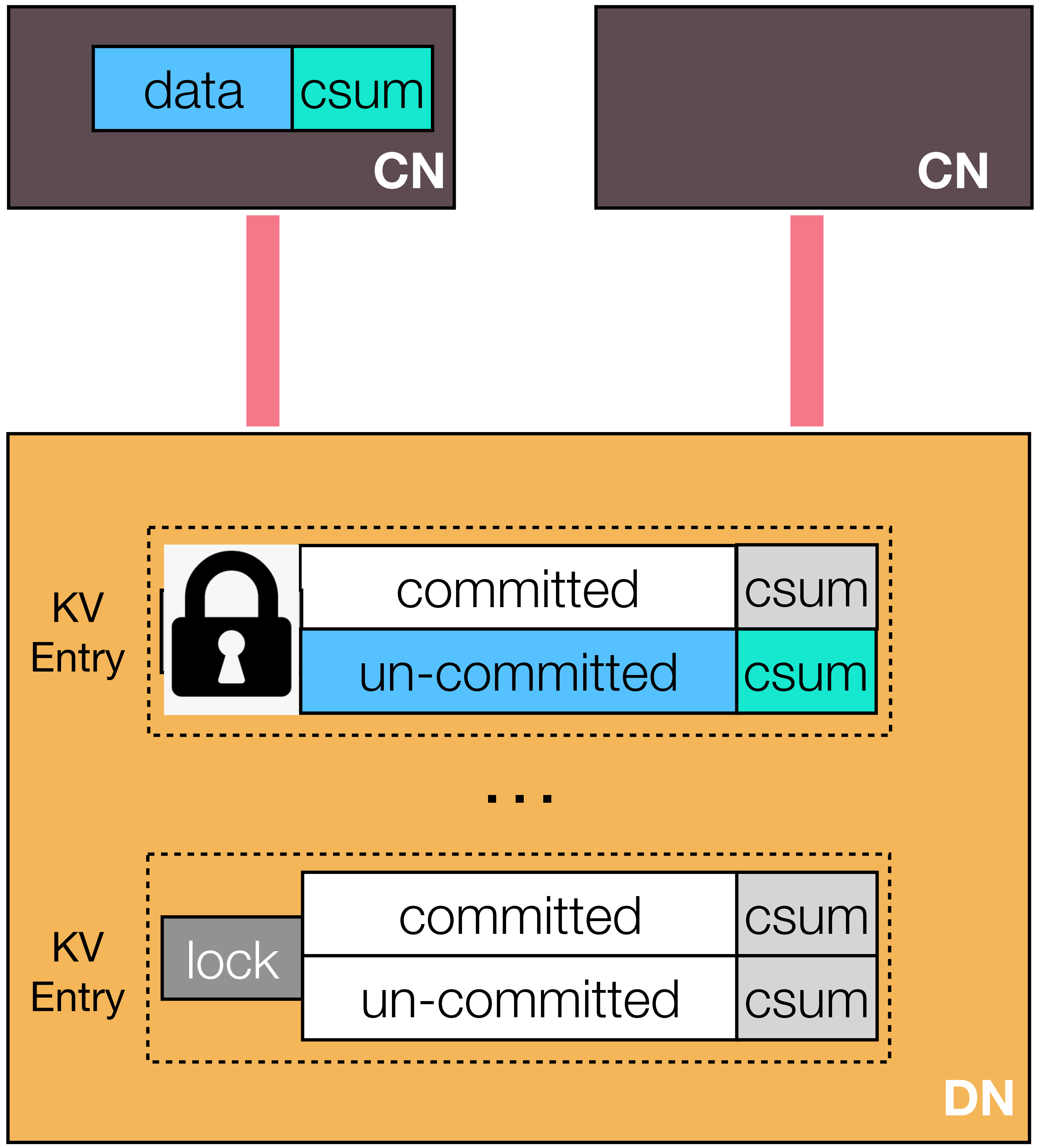

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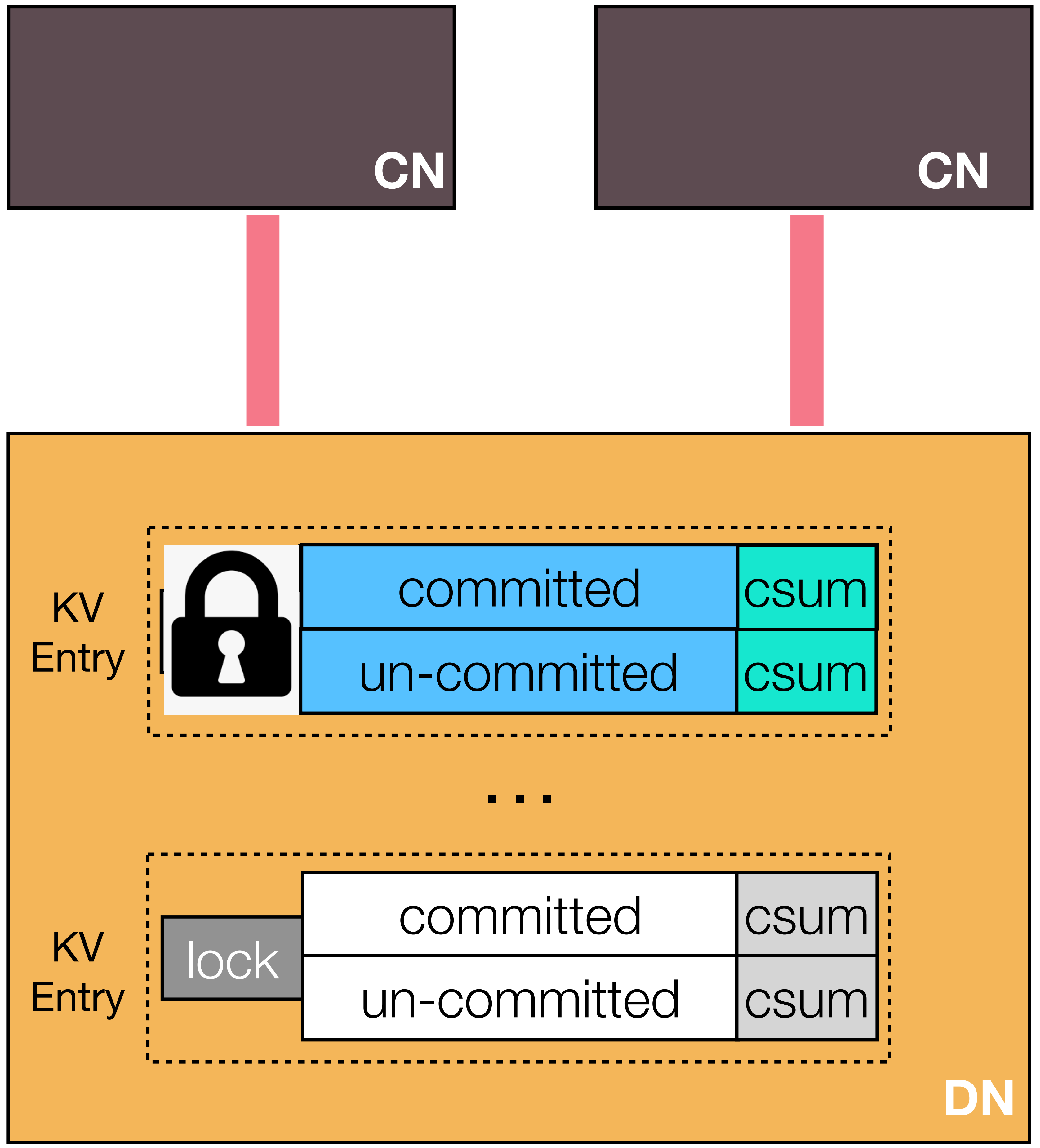

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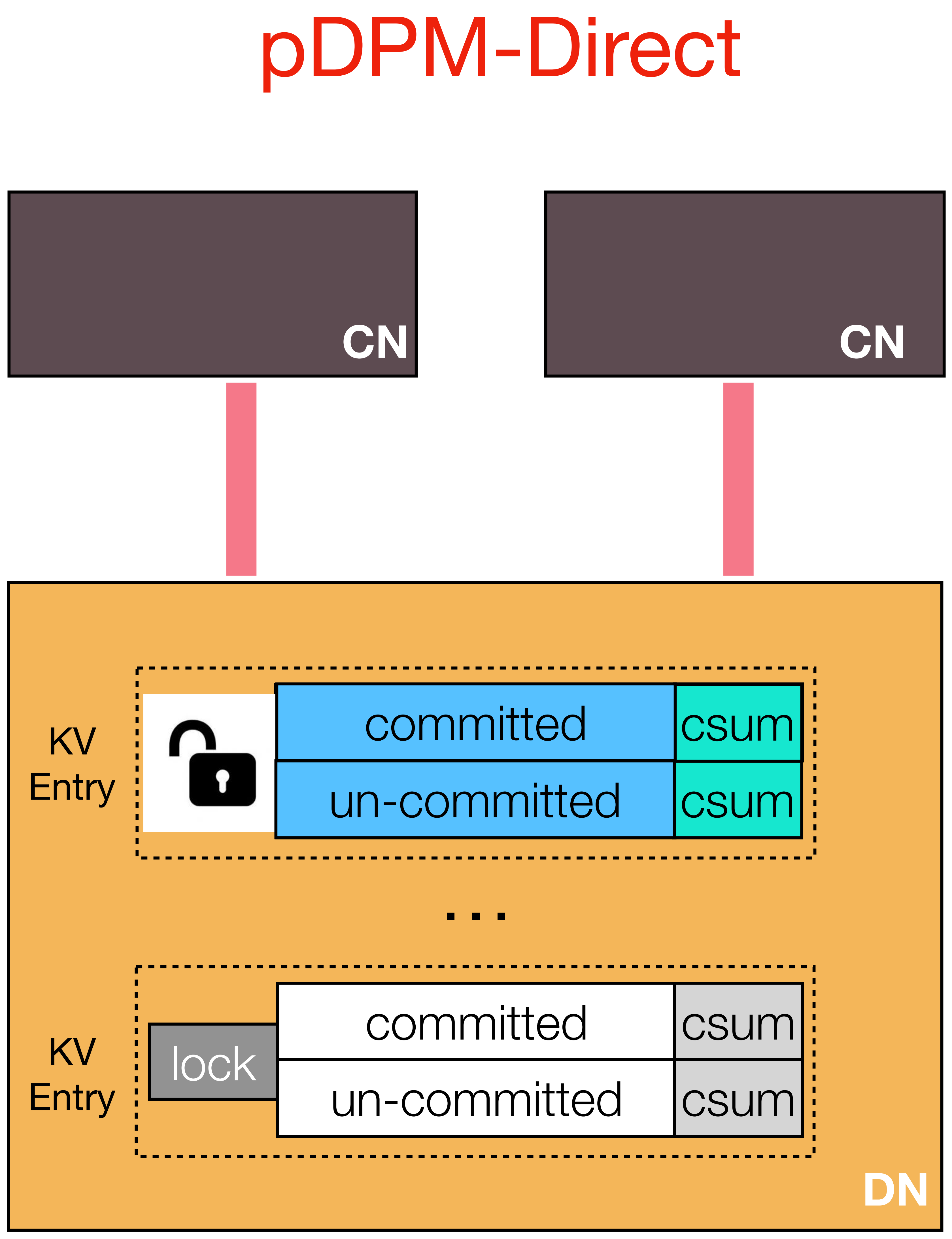

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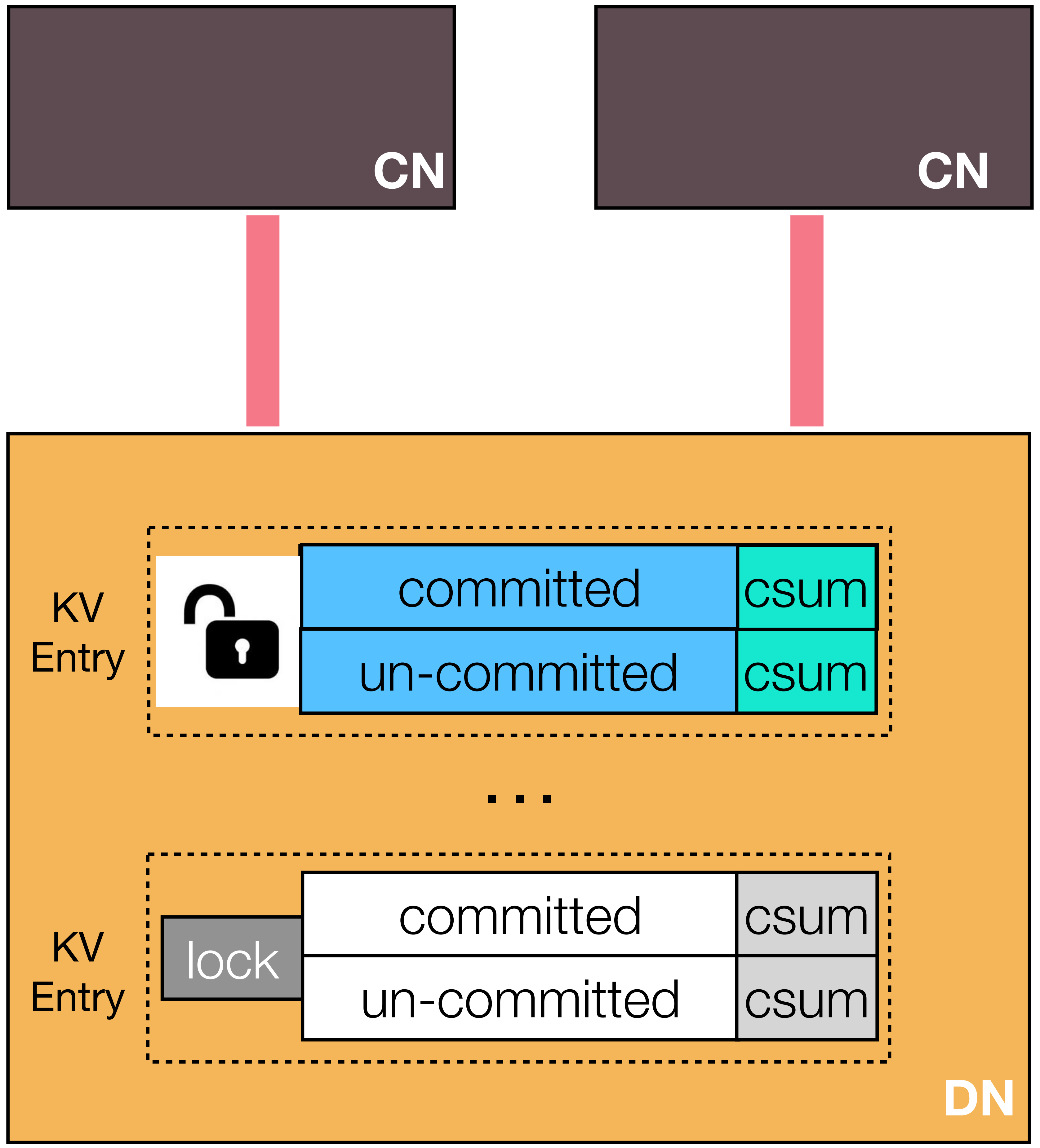

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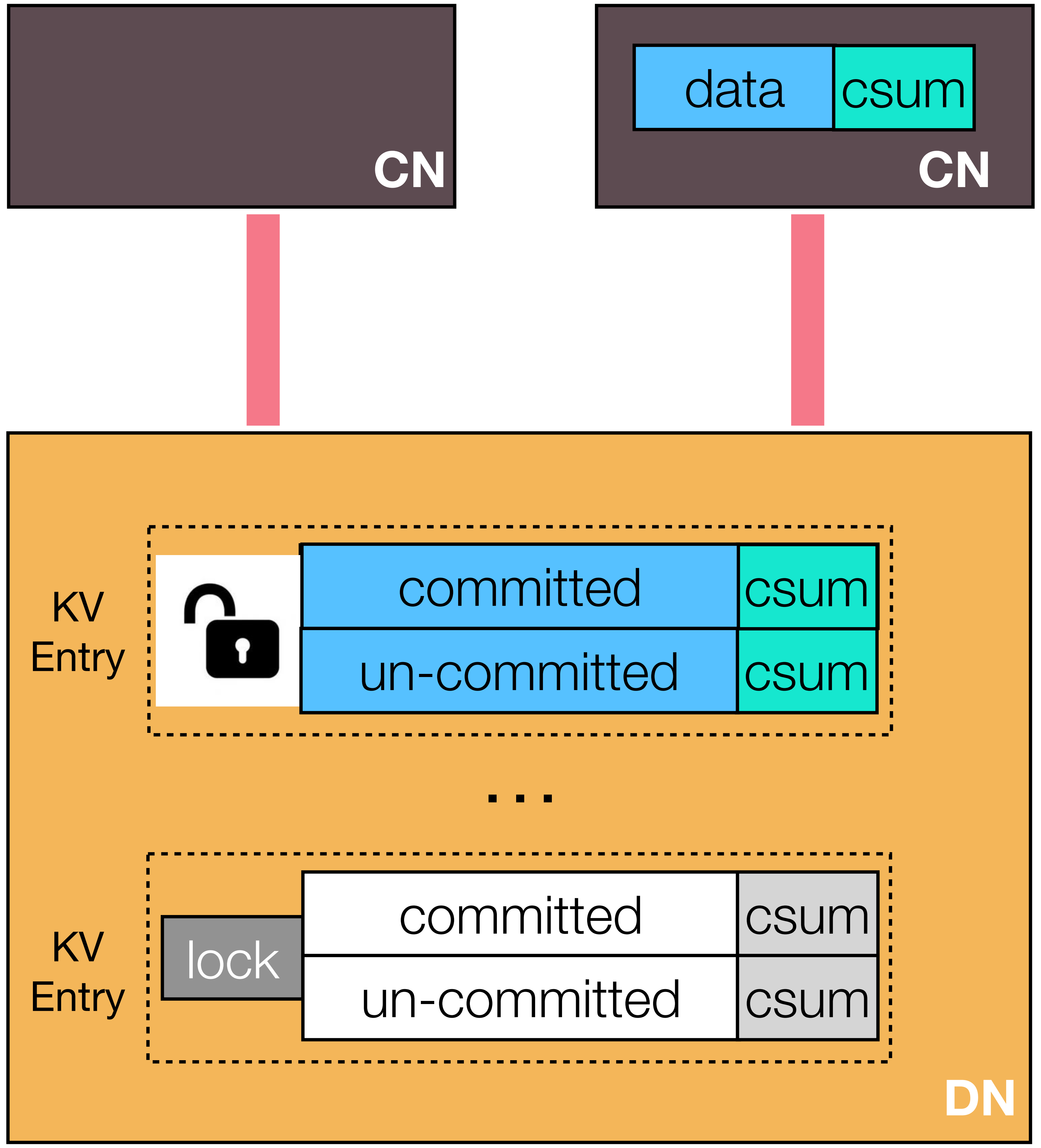

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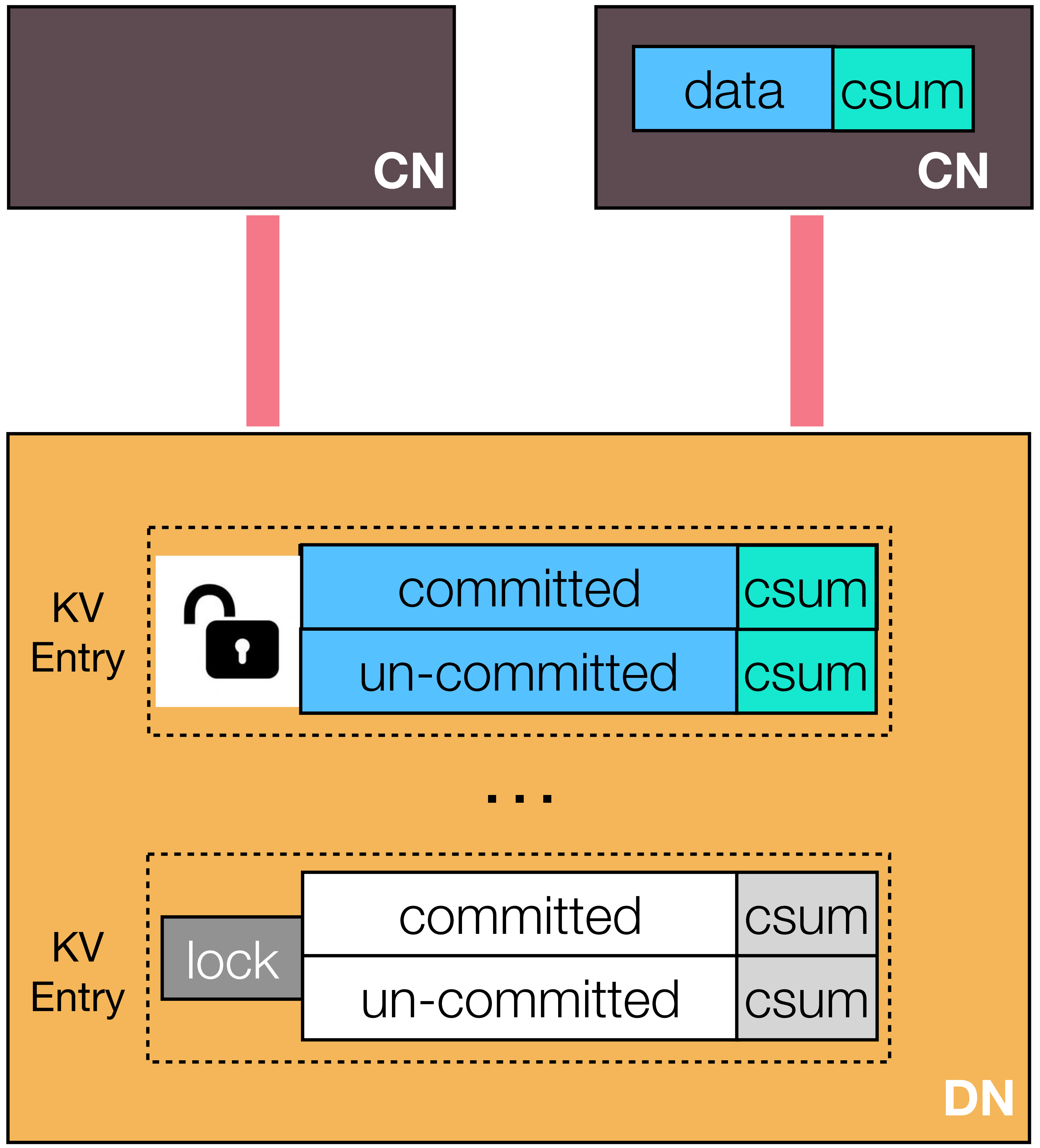

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Best case
Write: 4 RTT + csum calc
Read: 1 RTT + csum calc

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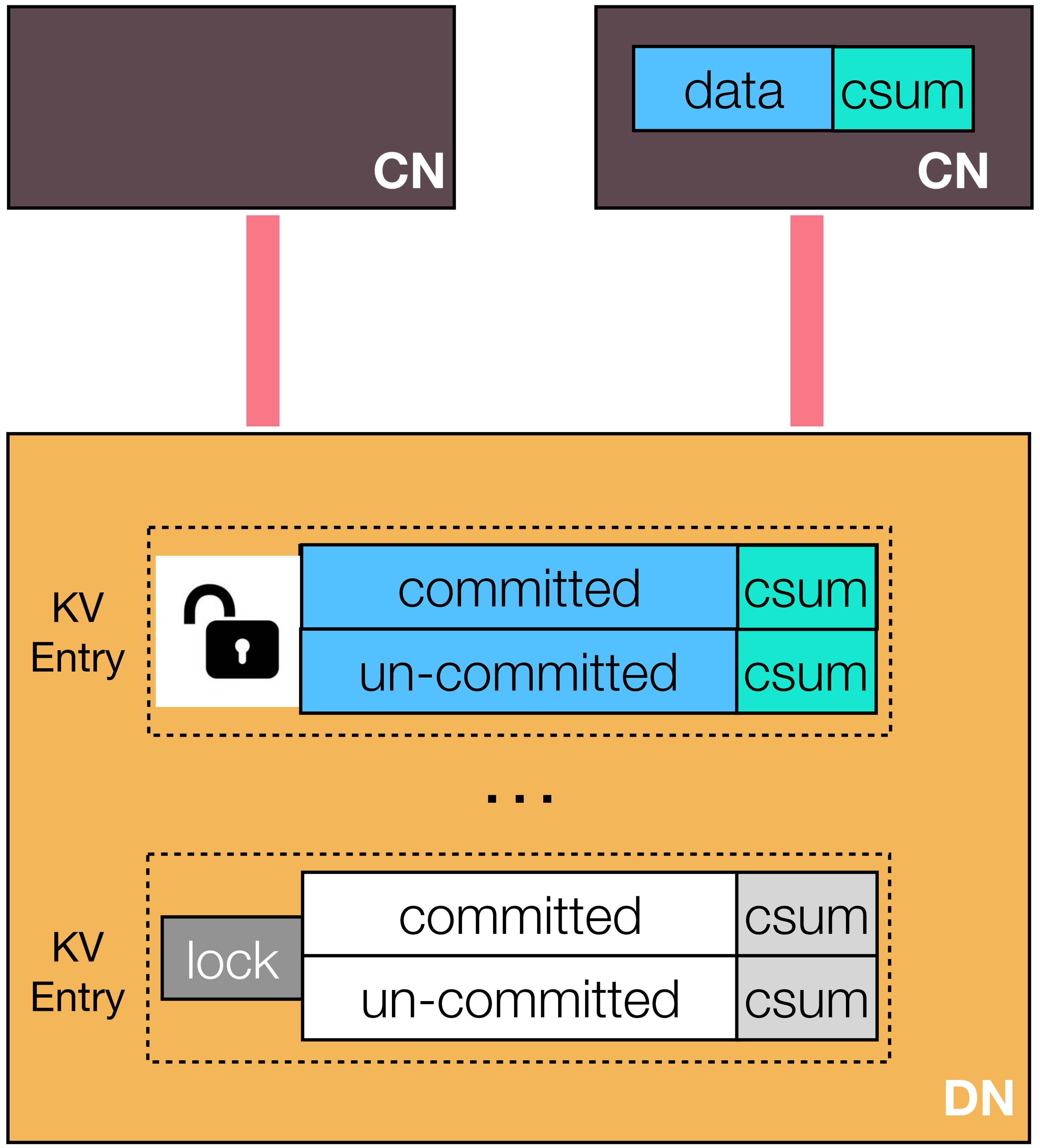

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Slow write
Slow with large data
Poor scalability under concurrent accesses

☹


Where to process and manage data?
pDPM-Direct
control
data access
CN
control
data access
CN
DN
DN
Clover
Metadata Server
control
data access
CN
data access
CN
DN
DN
pDPM-Central
data access
CN
data access
CN
Coordinator
control
coordinate access
DN
DN

- Slow write
- Slow for large data

Distributed data & metadata planes

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Distributed data & metadata planes

Centralized data & metadata planes

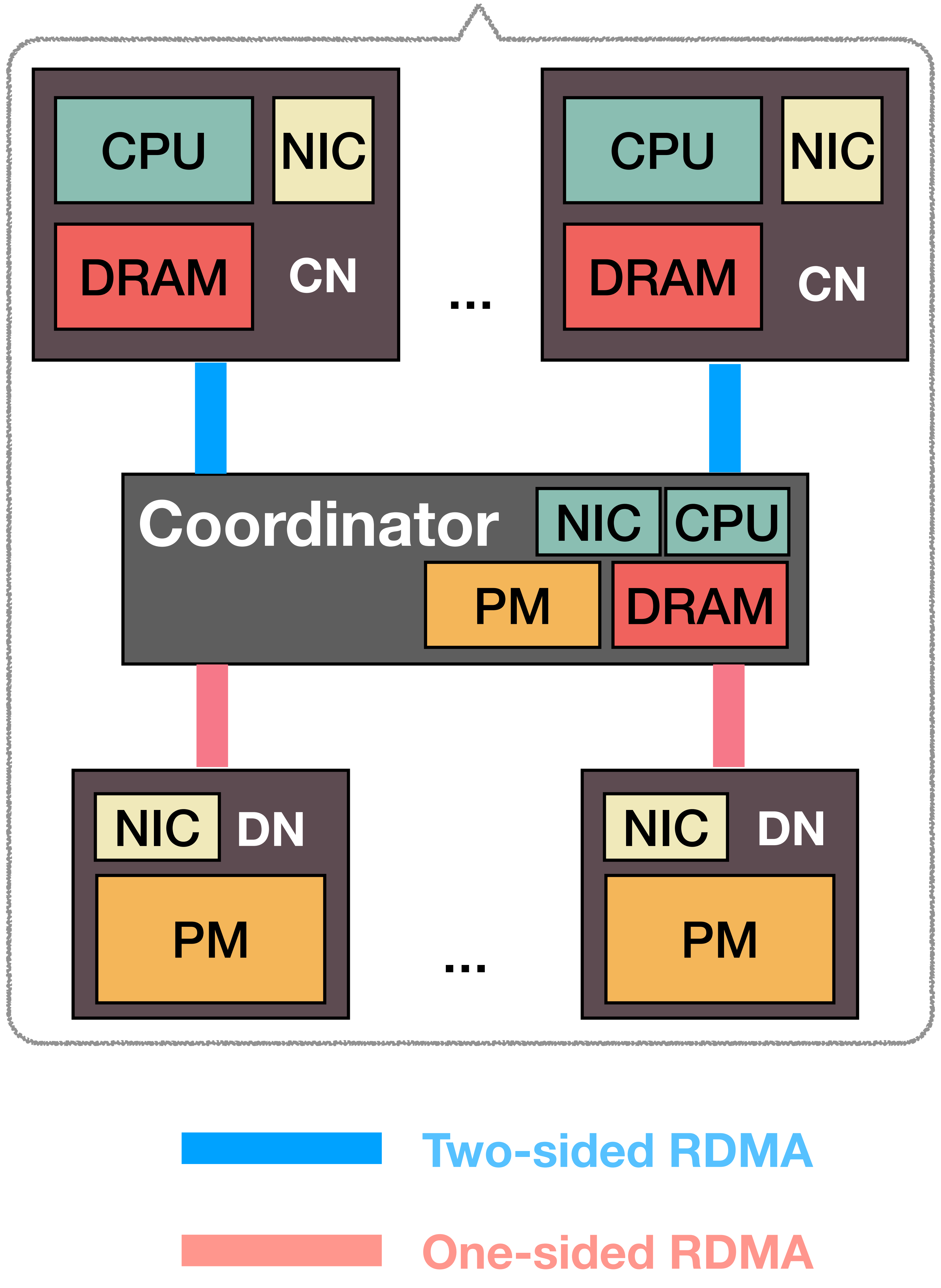
pDPM-Central: A Central Coordinator between CNs and DNs

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



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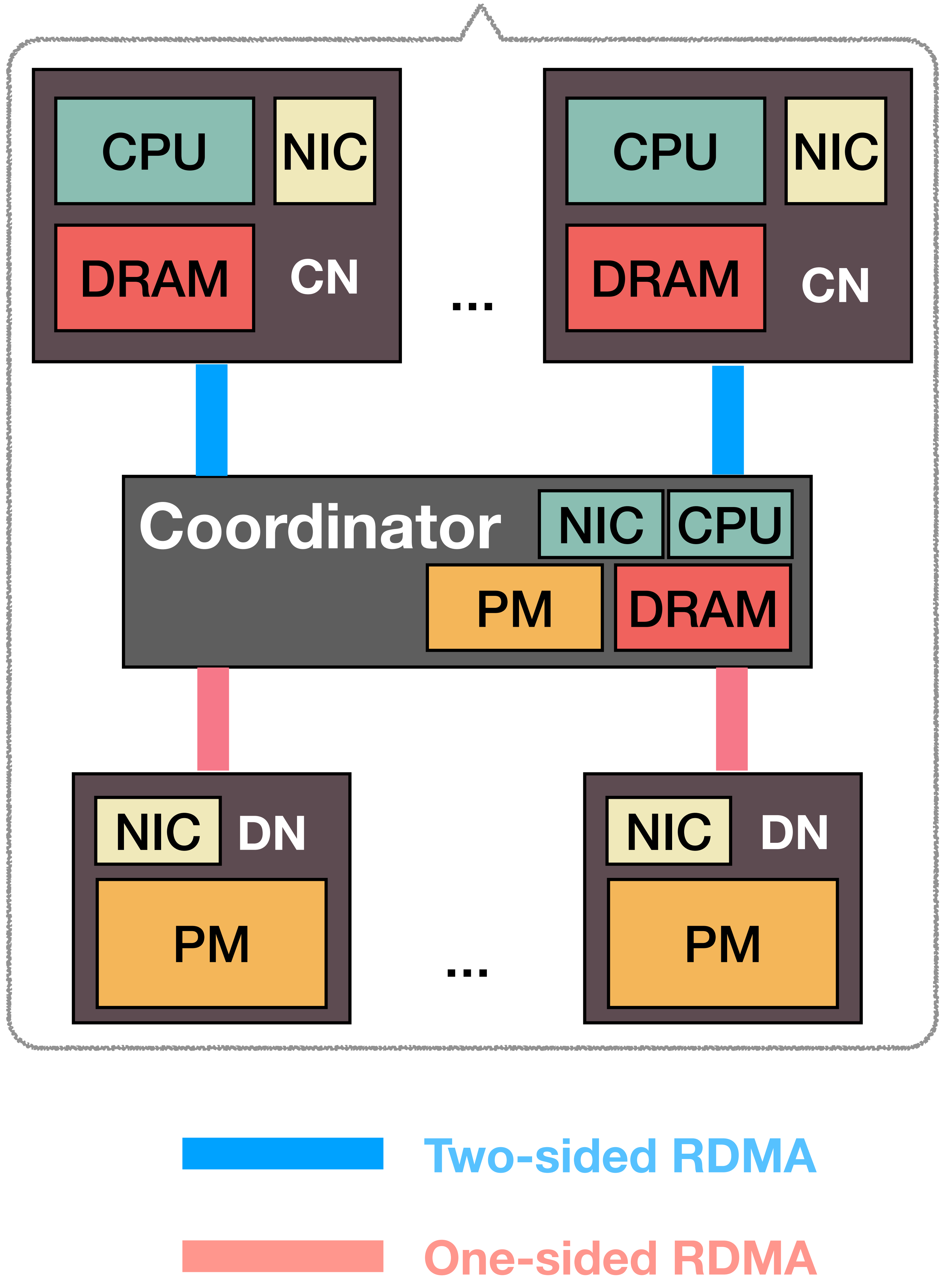
Easier to manage DNs and coordinate concurrent accesses



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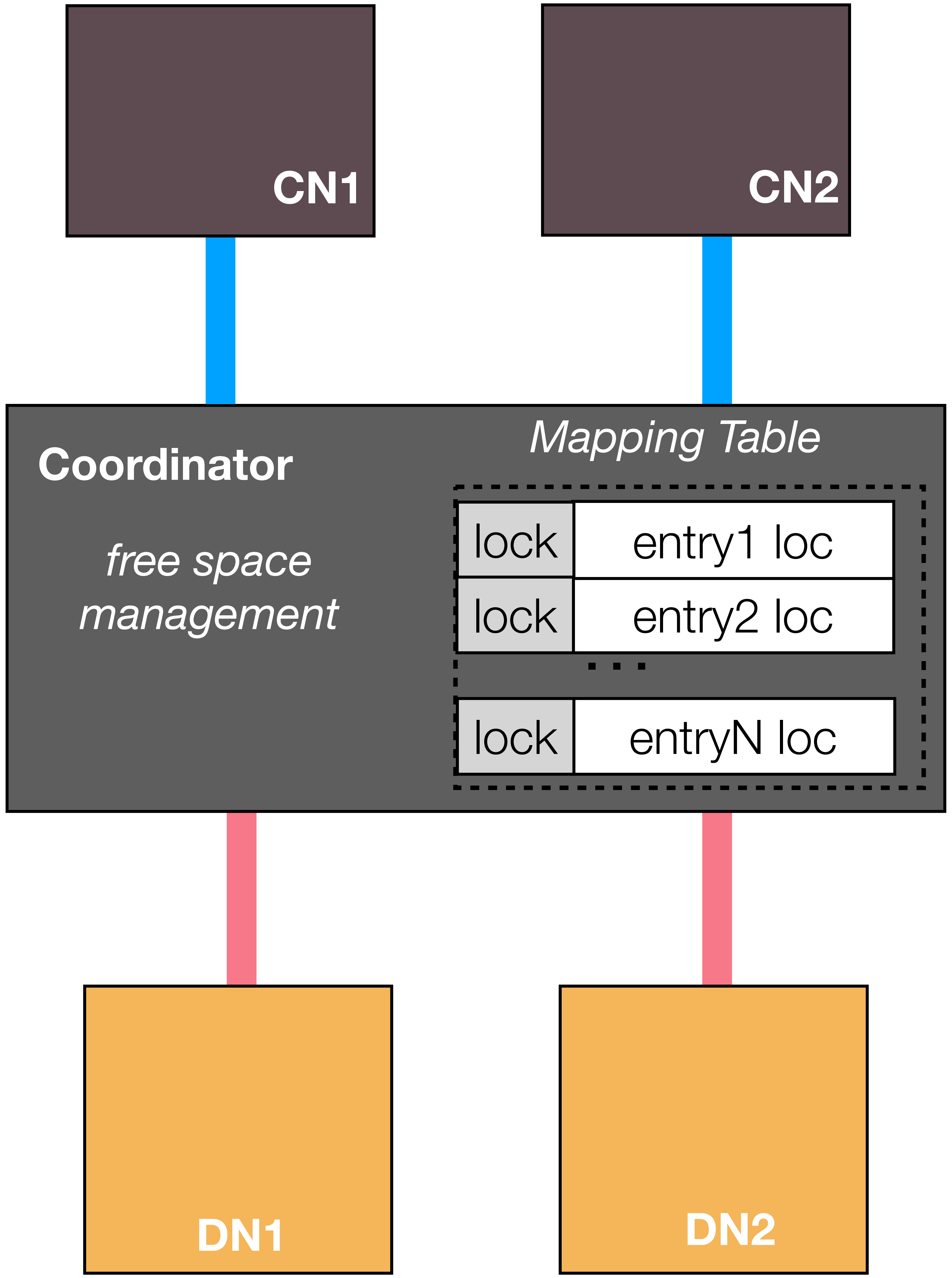

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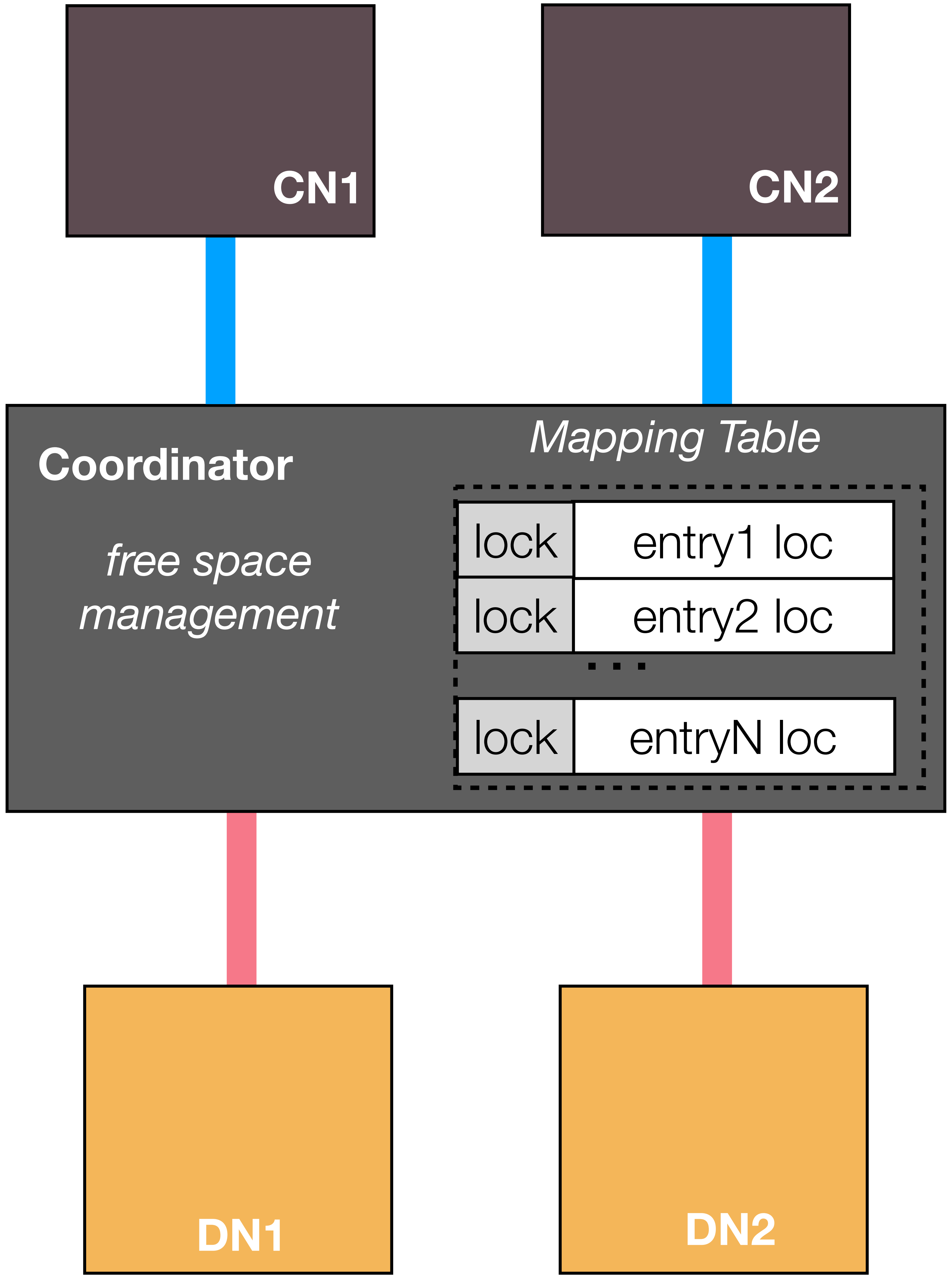

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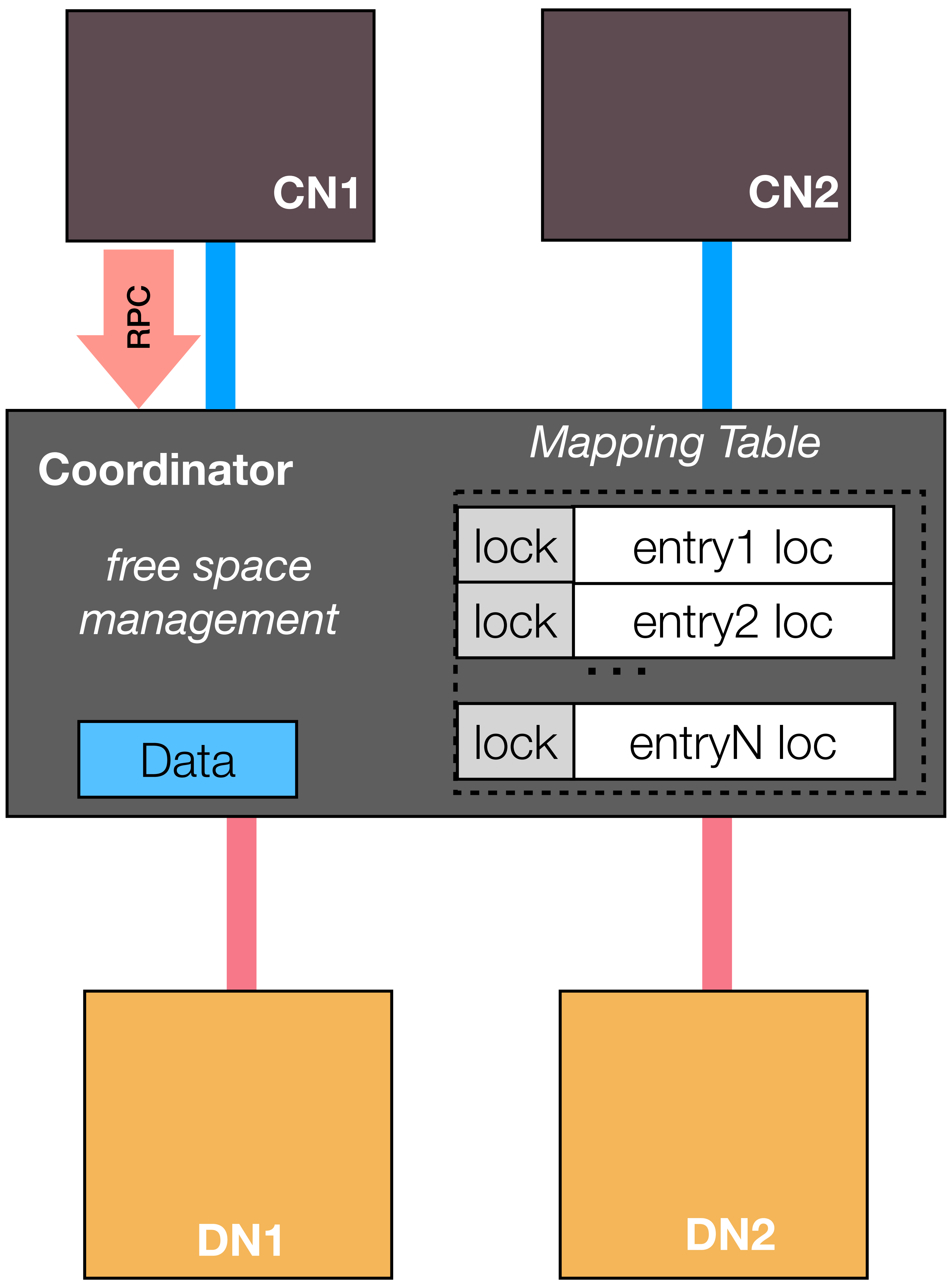

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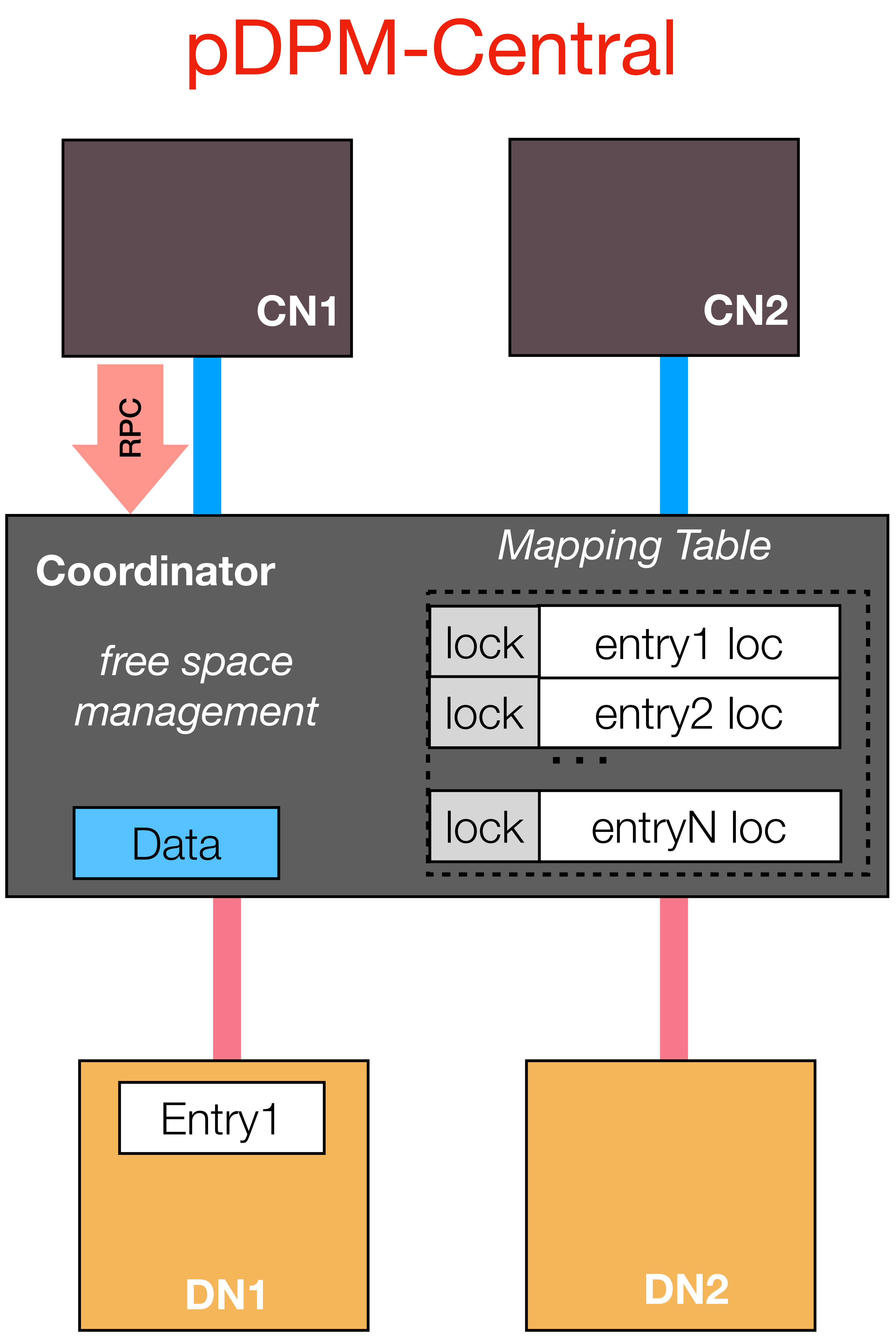

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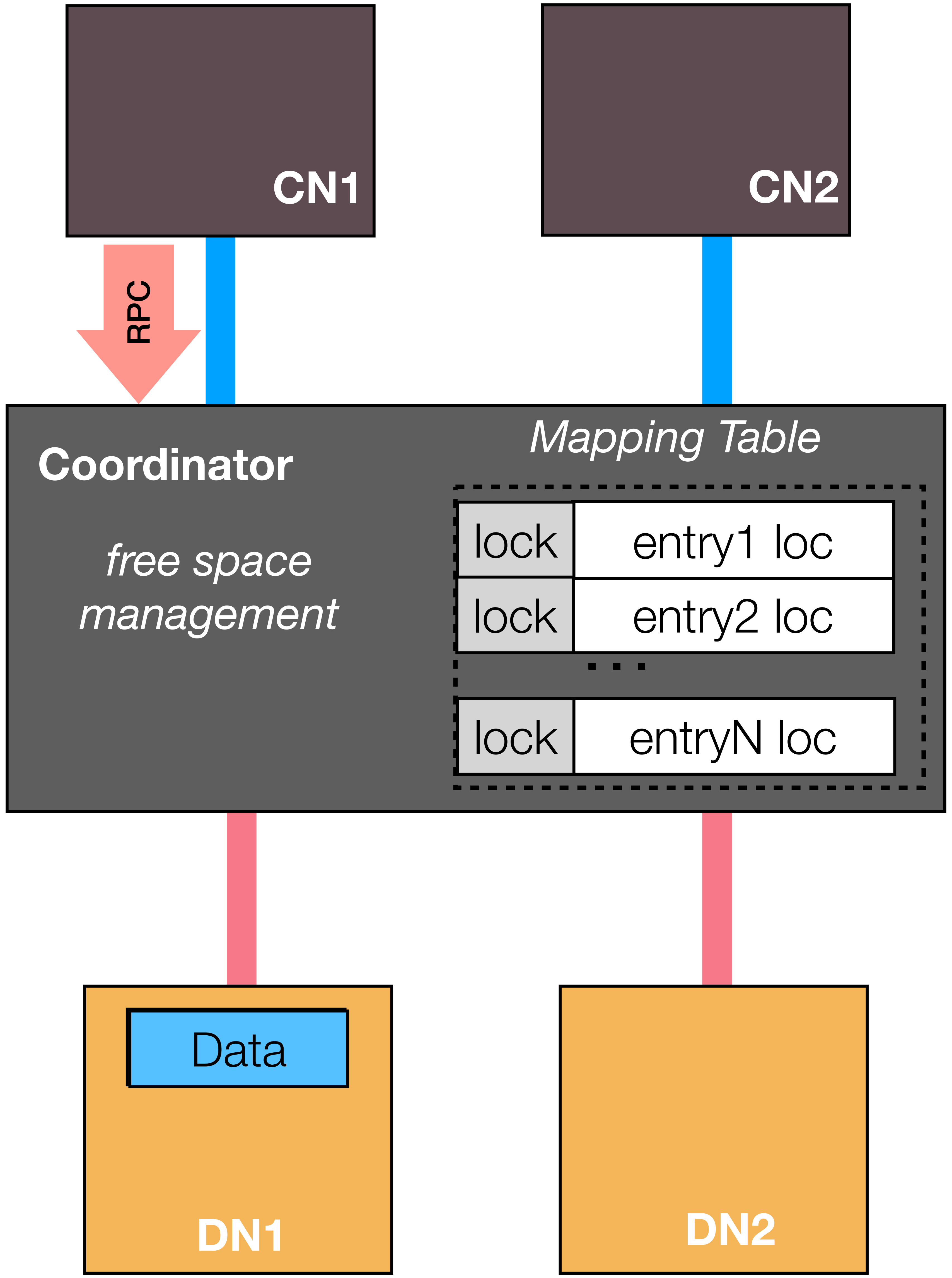

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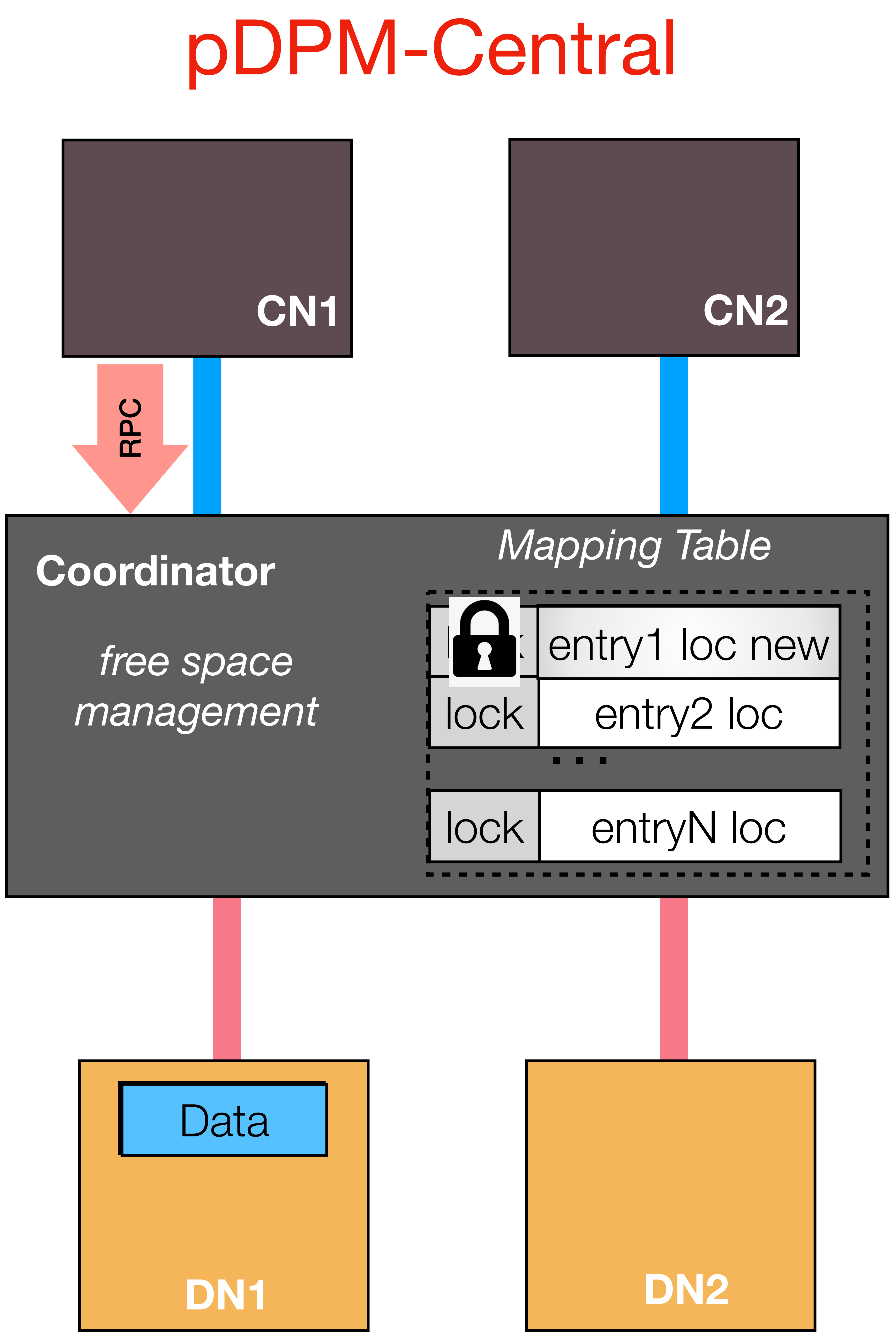

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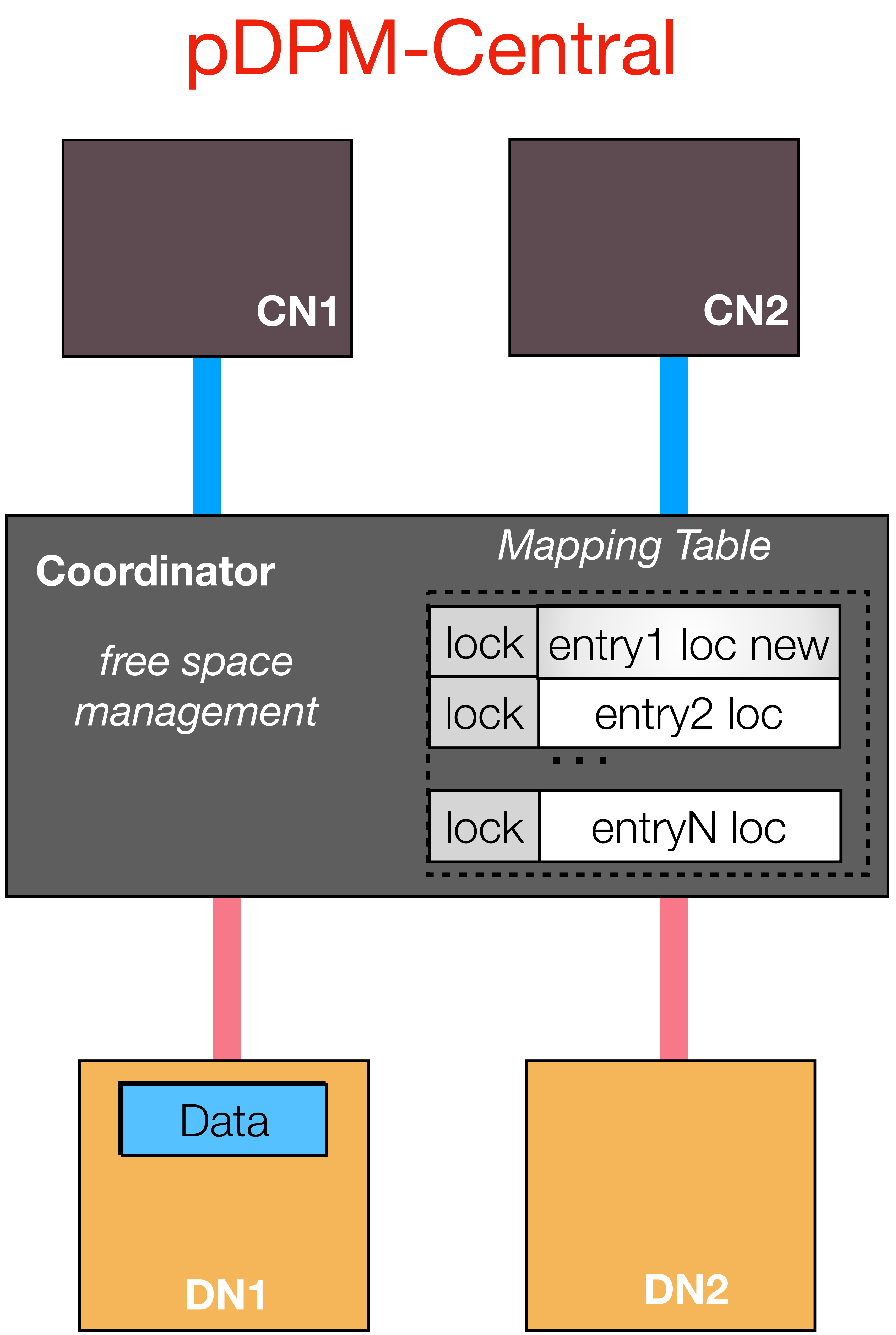

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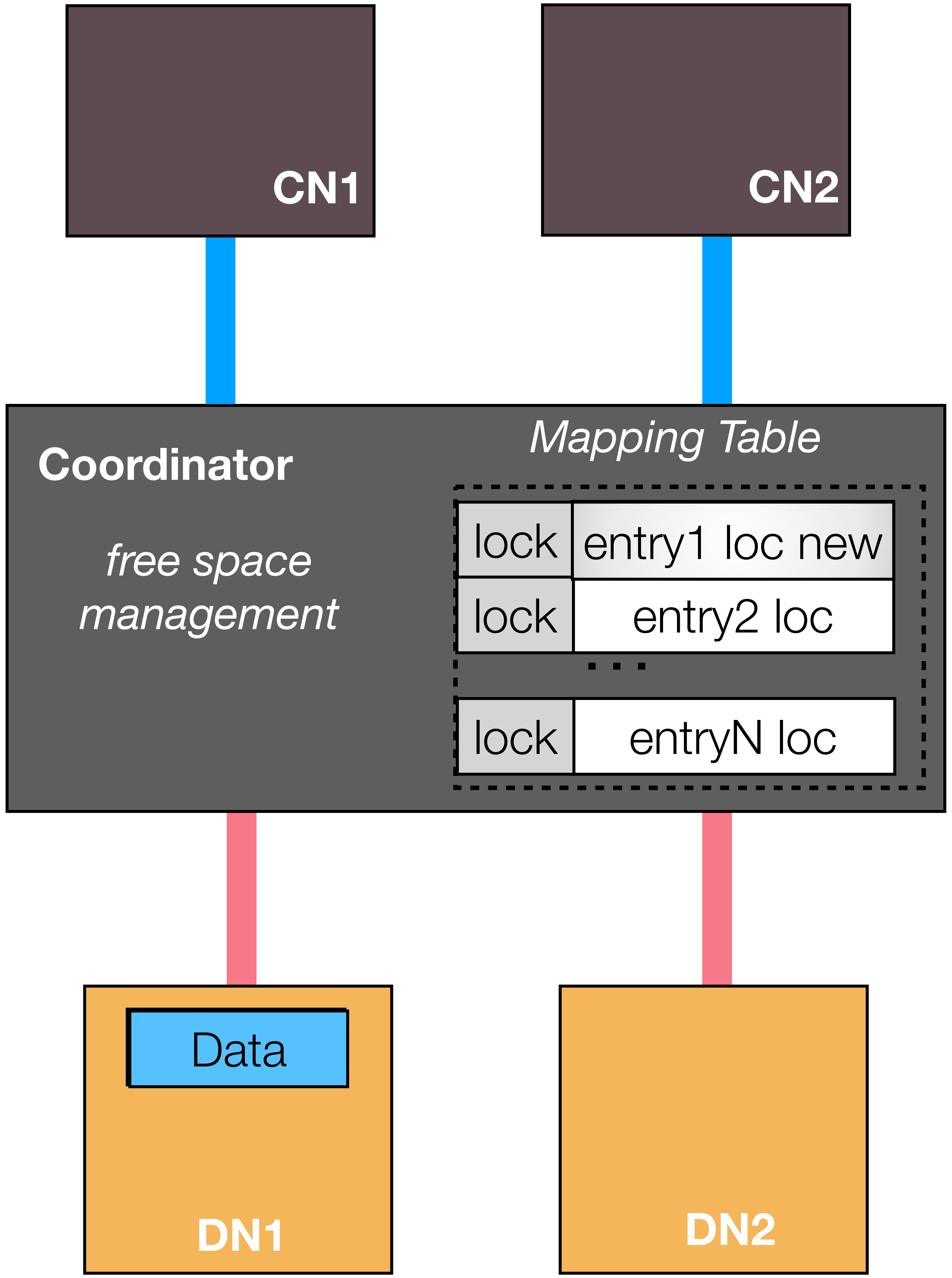

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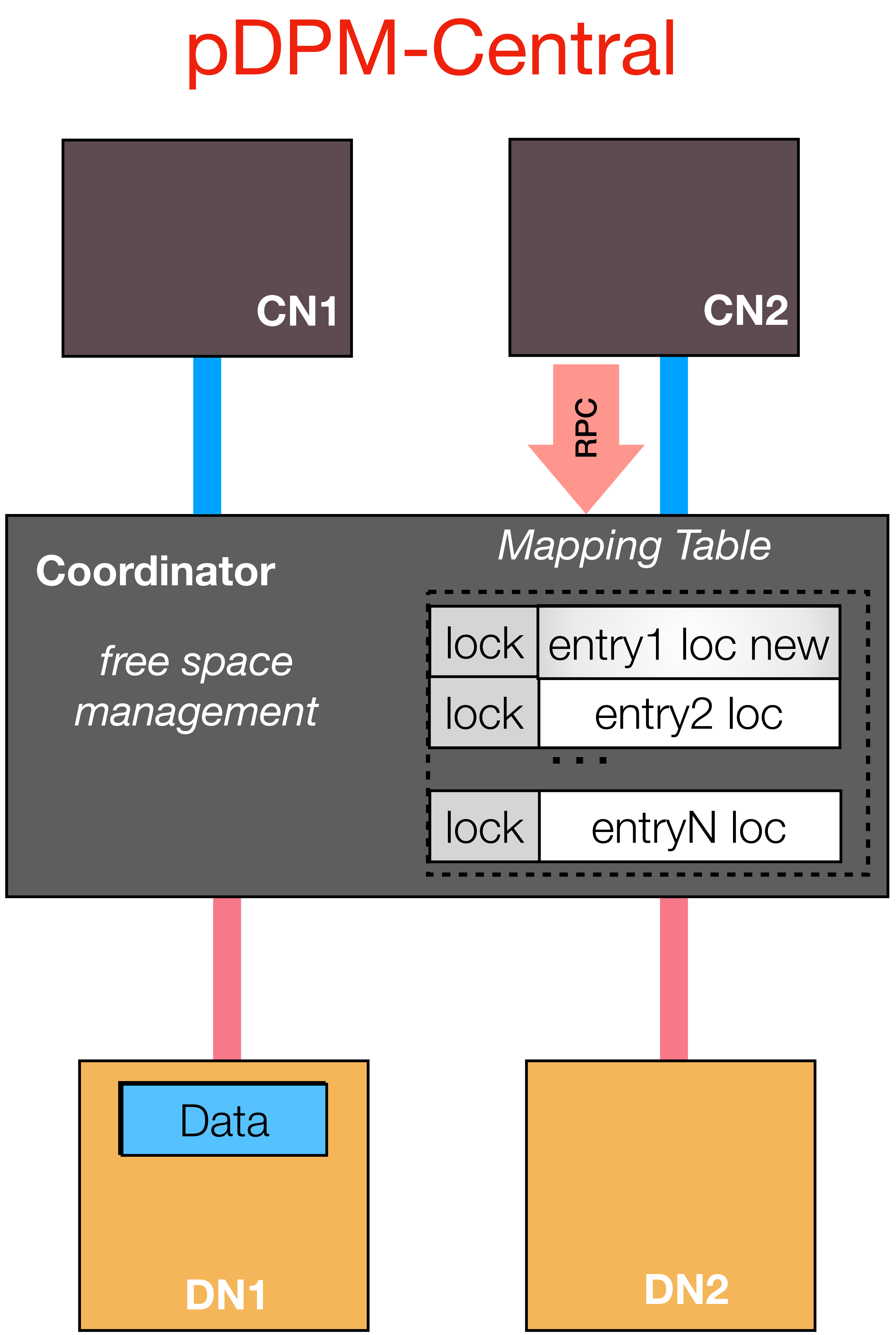

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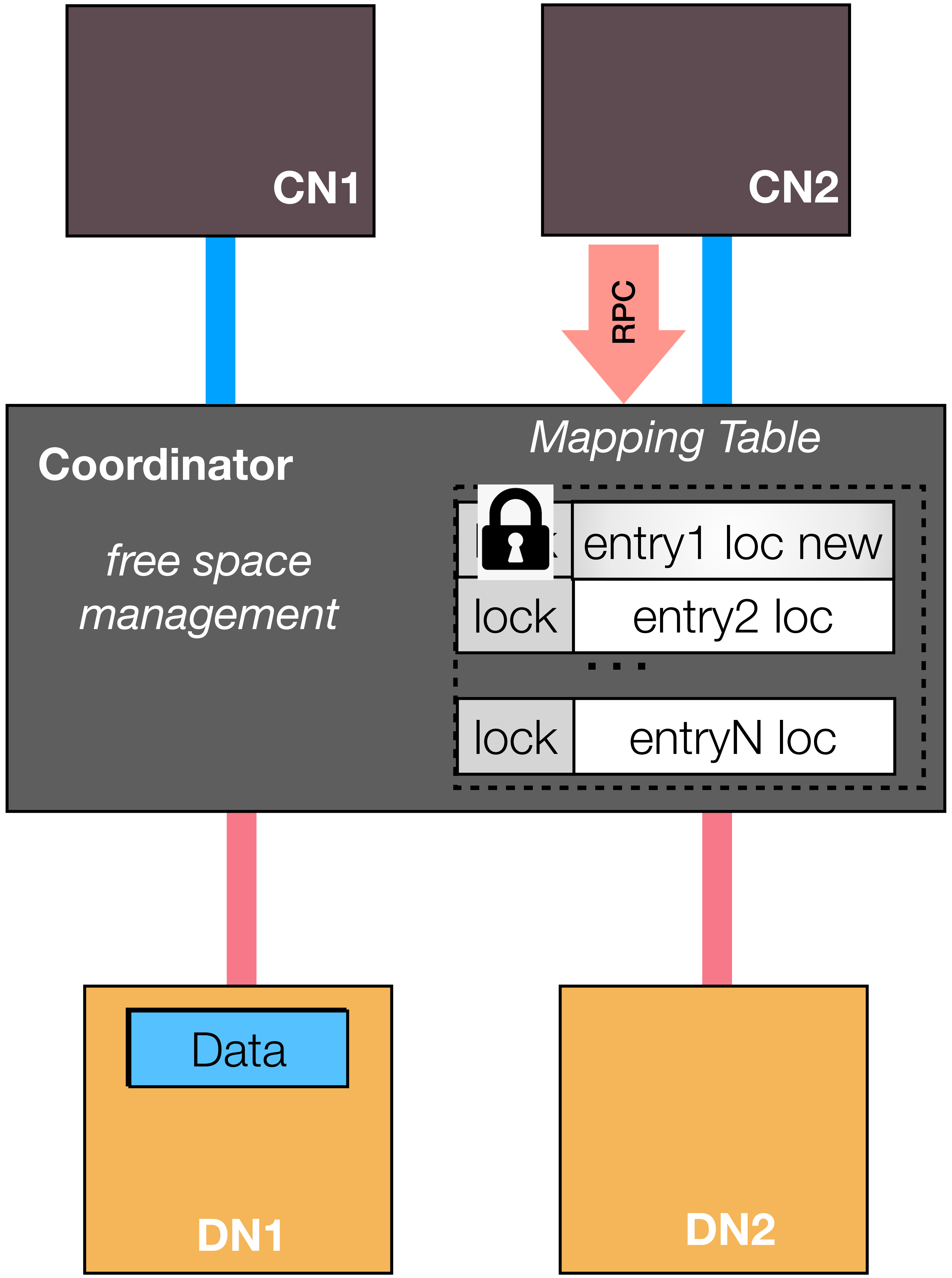

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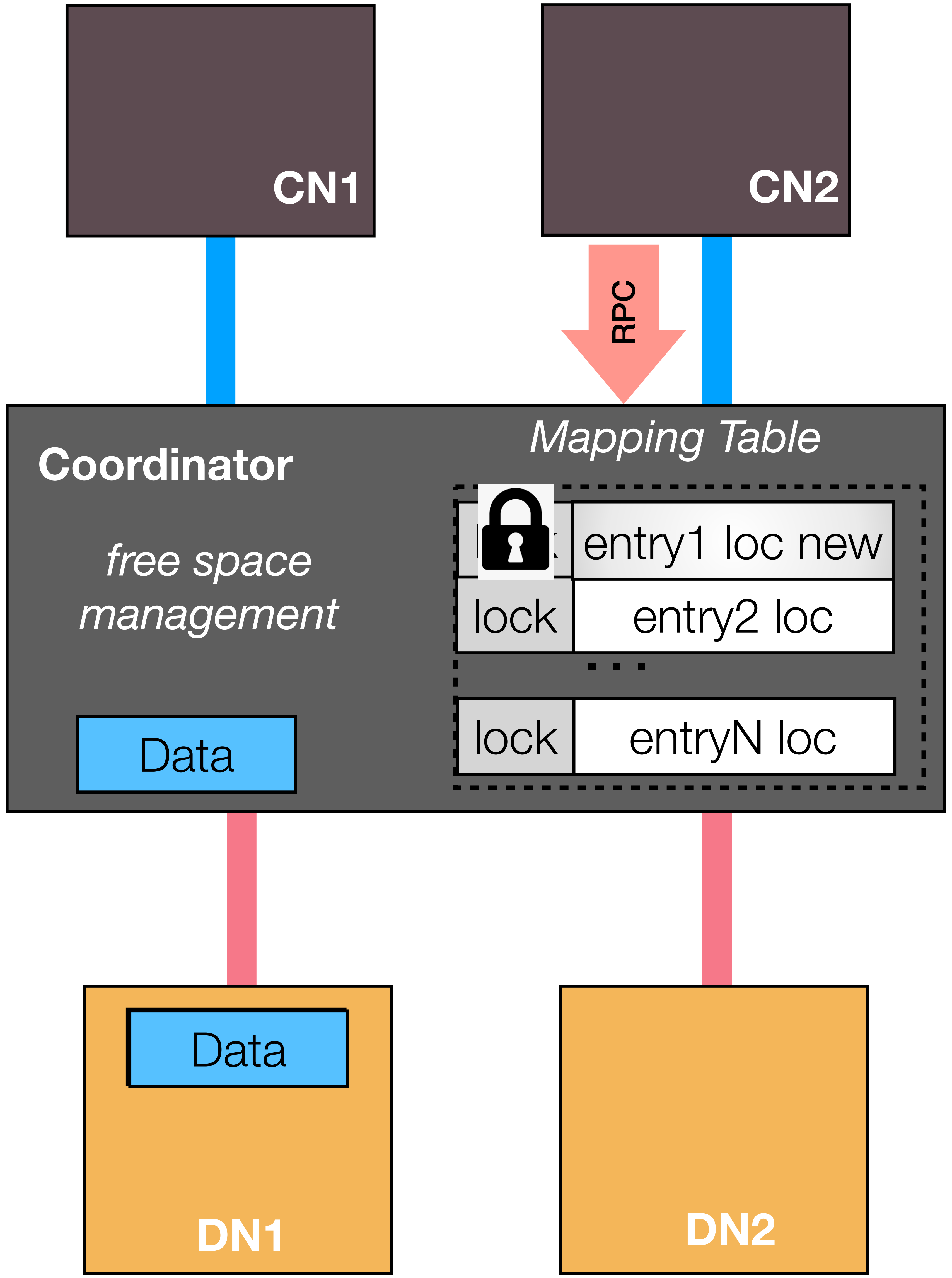

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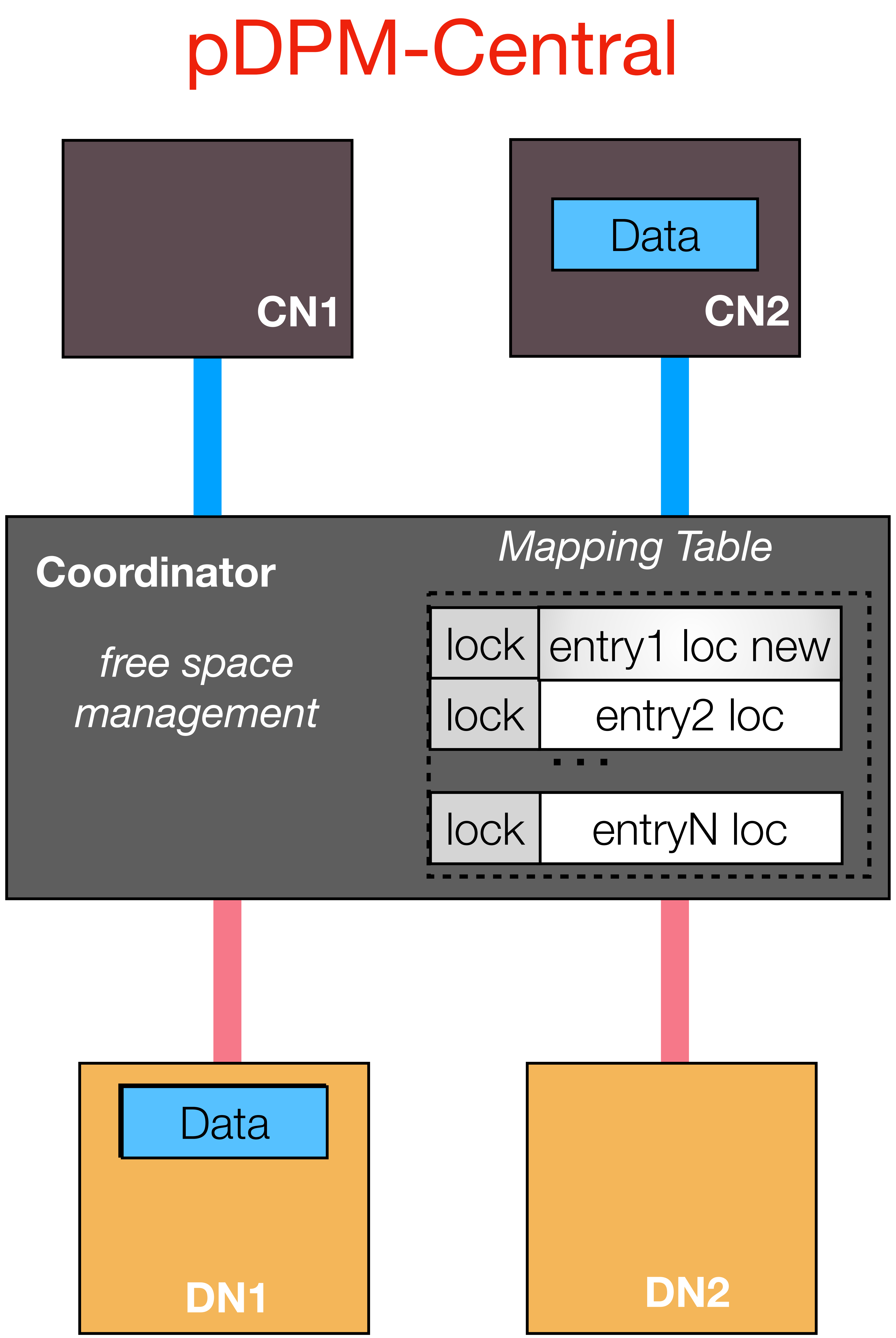

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Read: 2 RTTs
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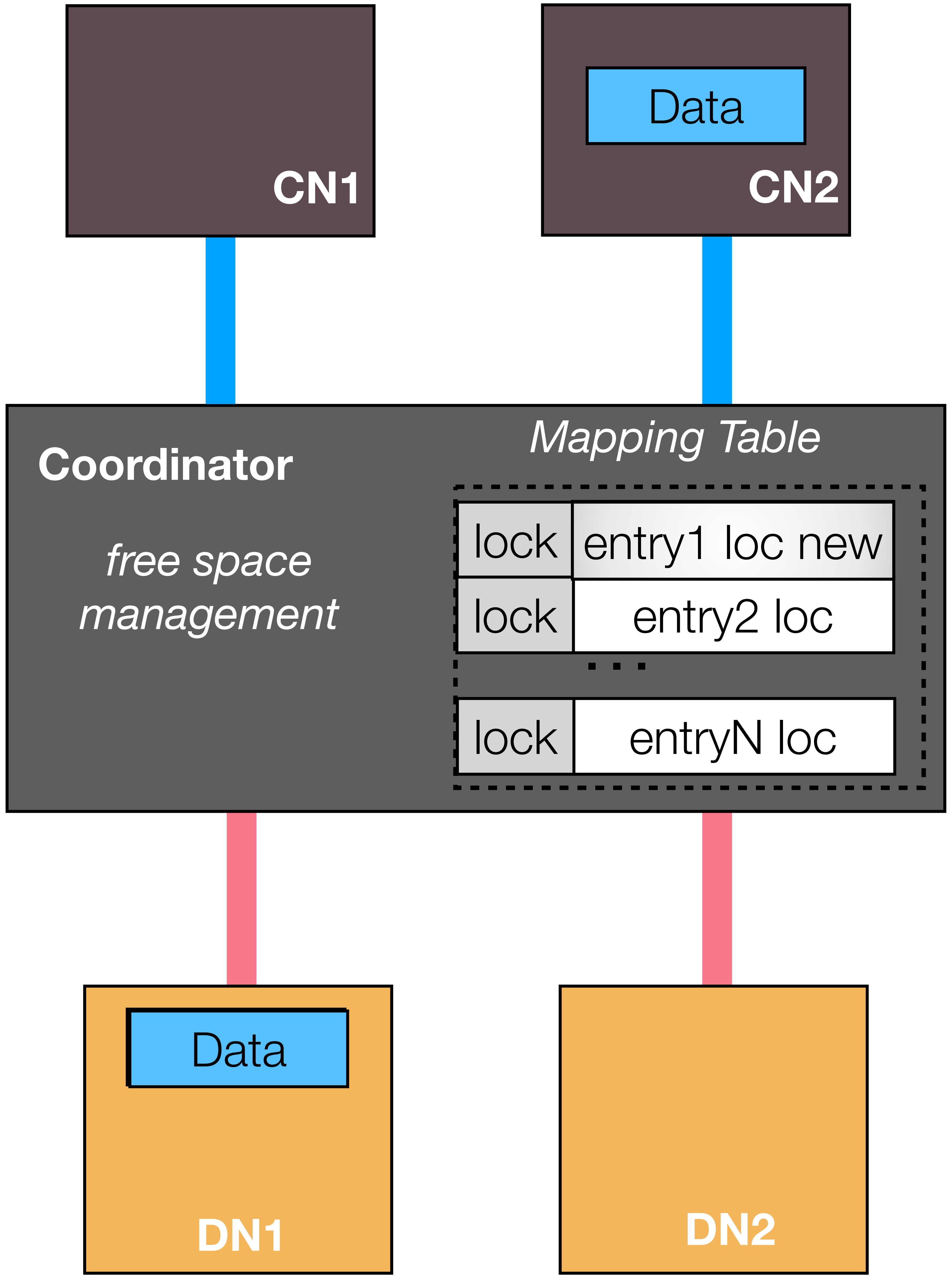

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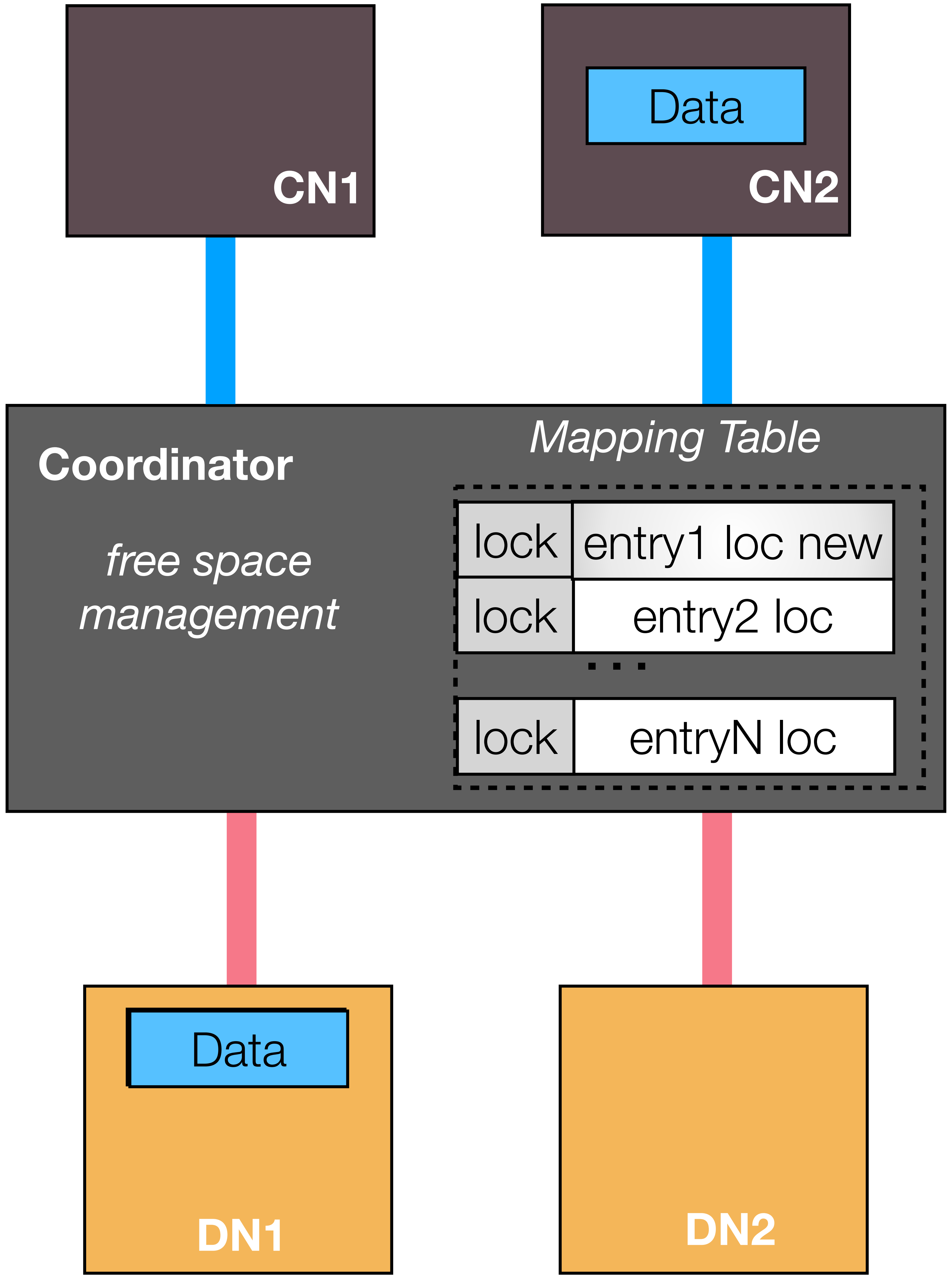
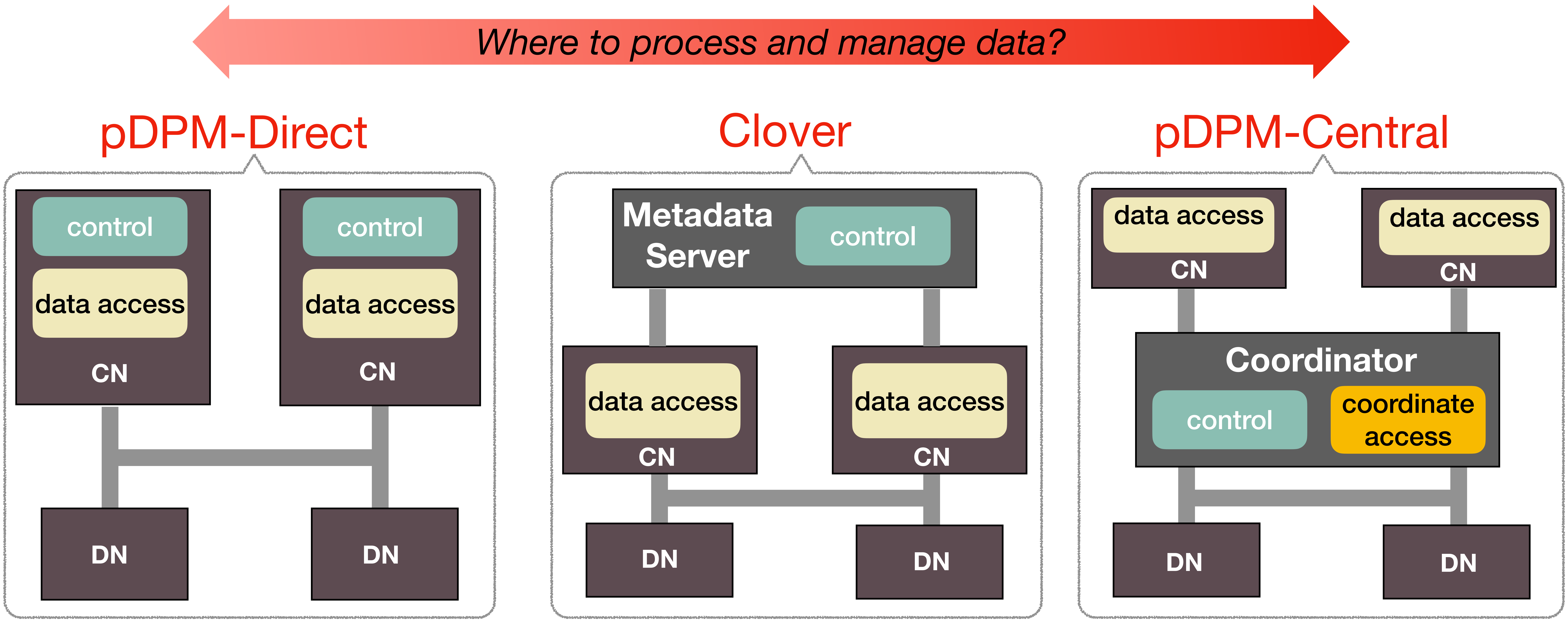
☹ **Slower read**
Poor scalability: coordinator is the bottleneck

pDPM-Central

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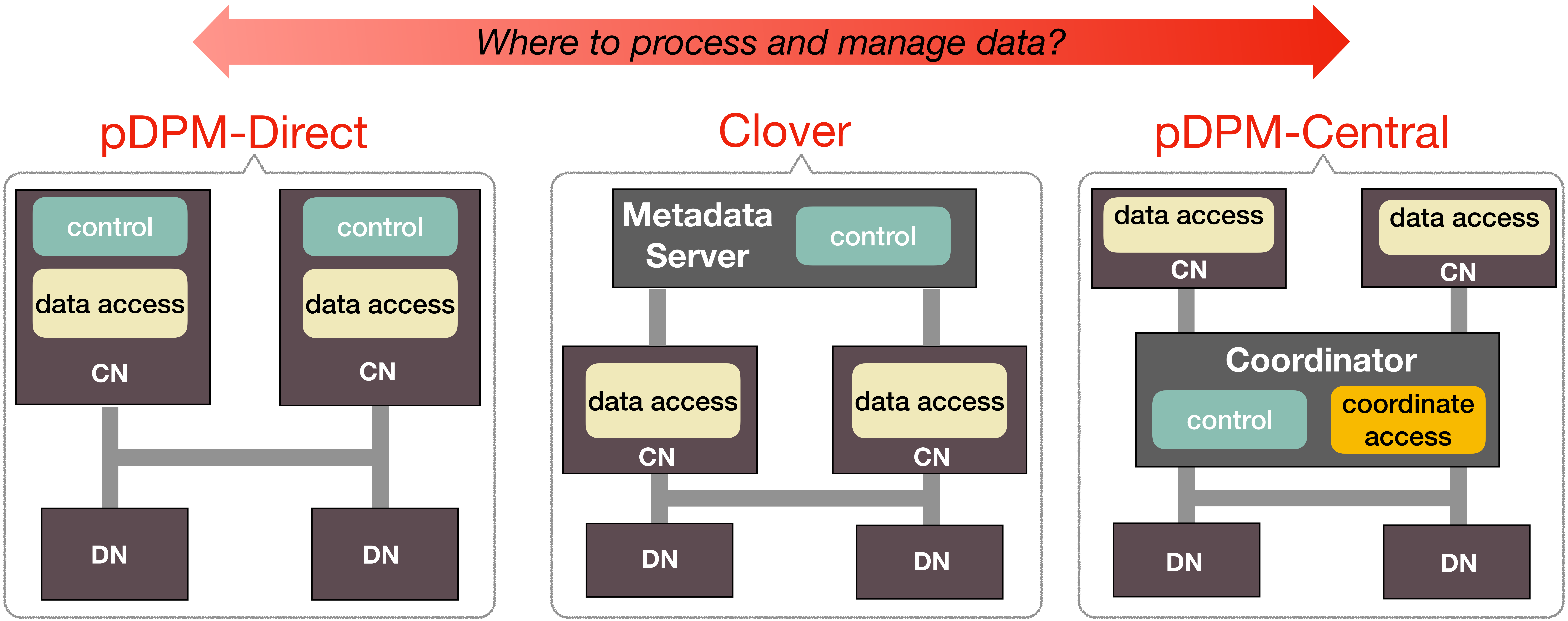

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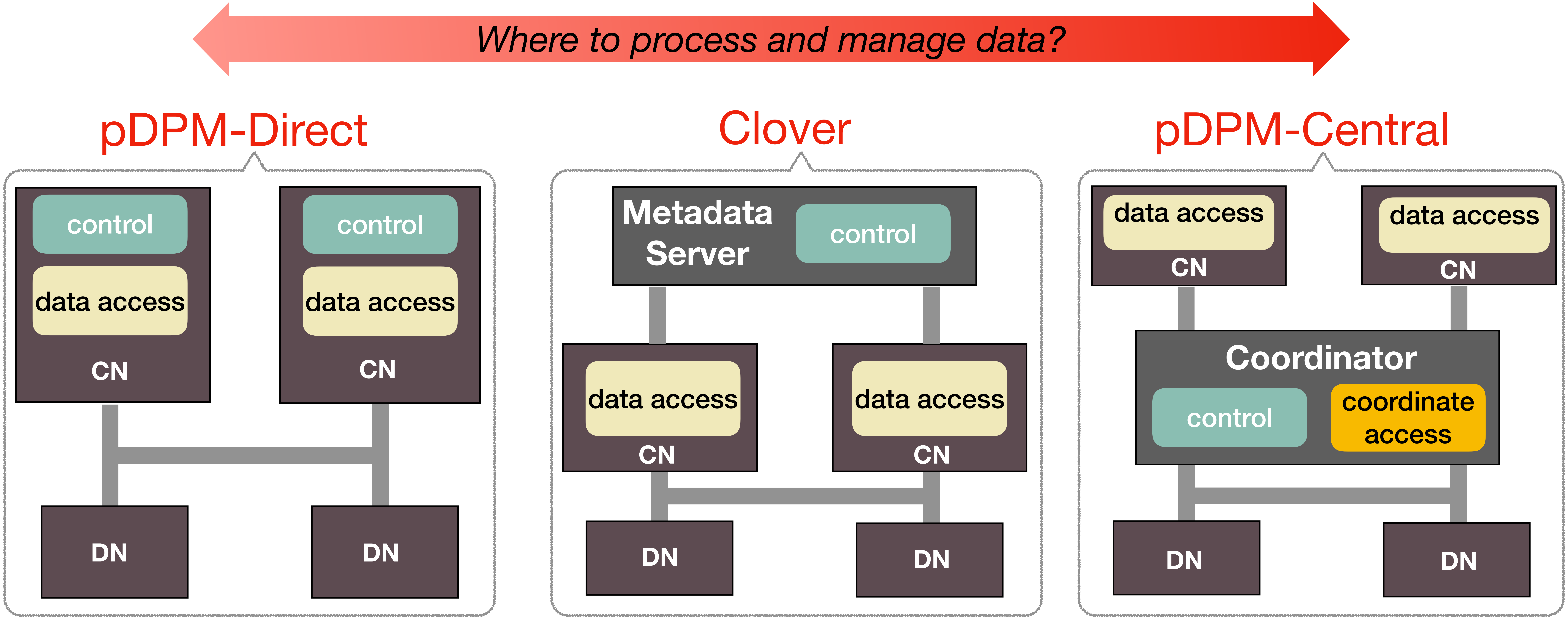

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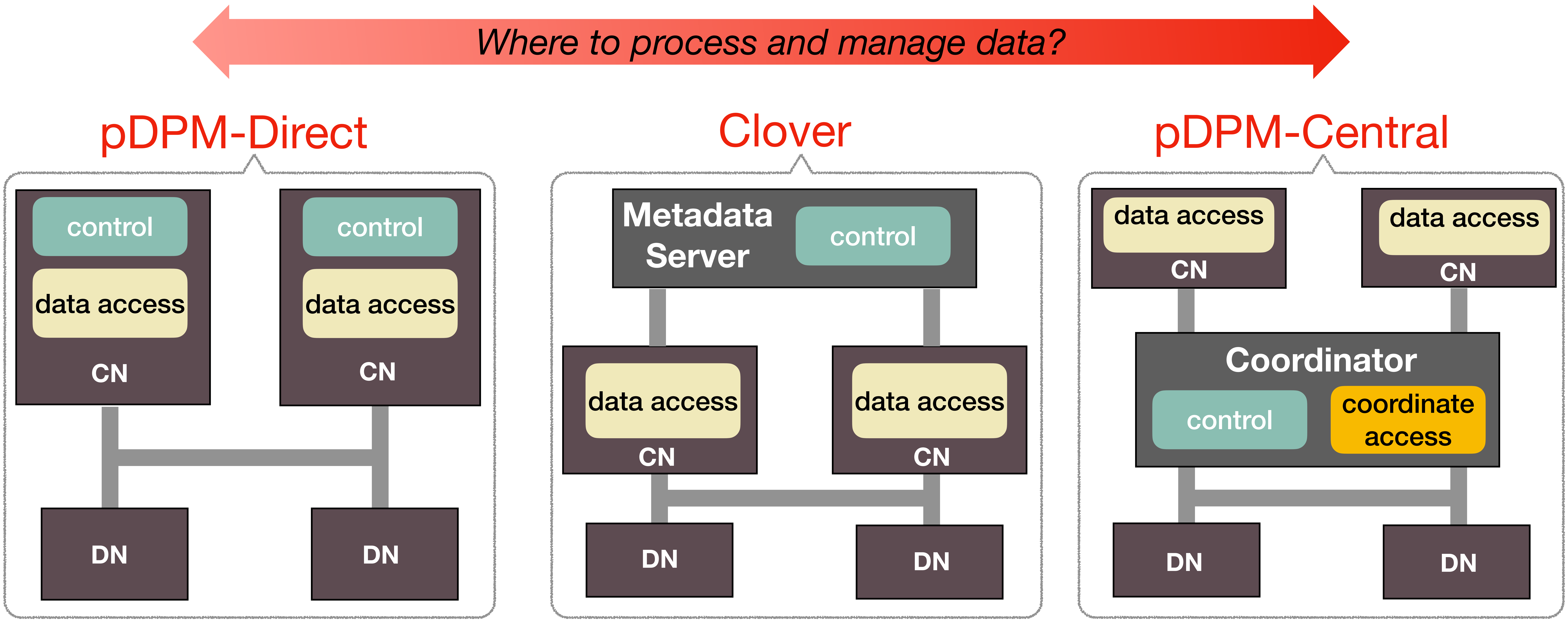

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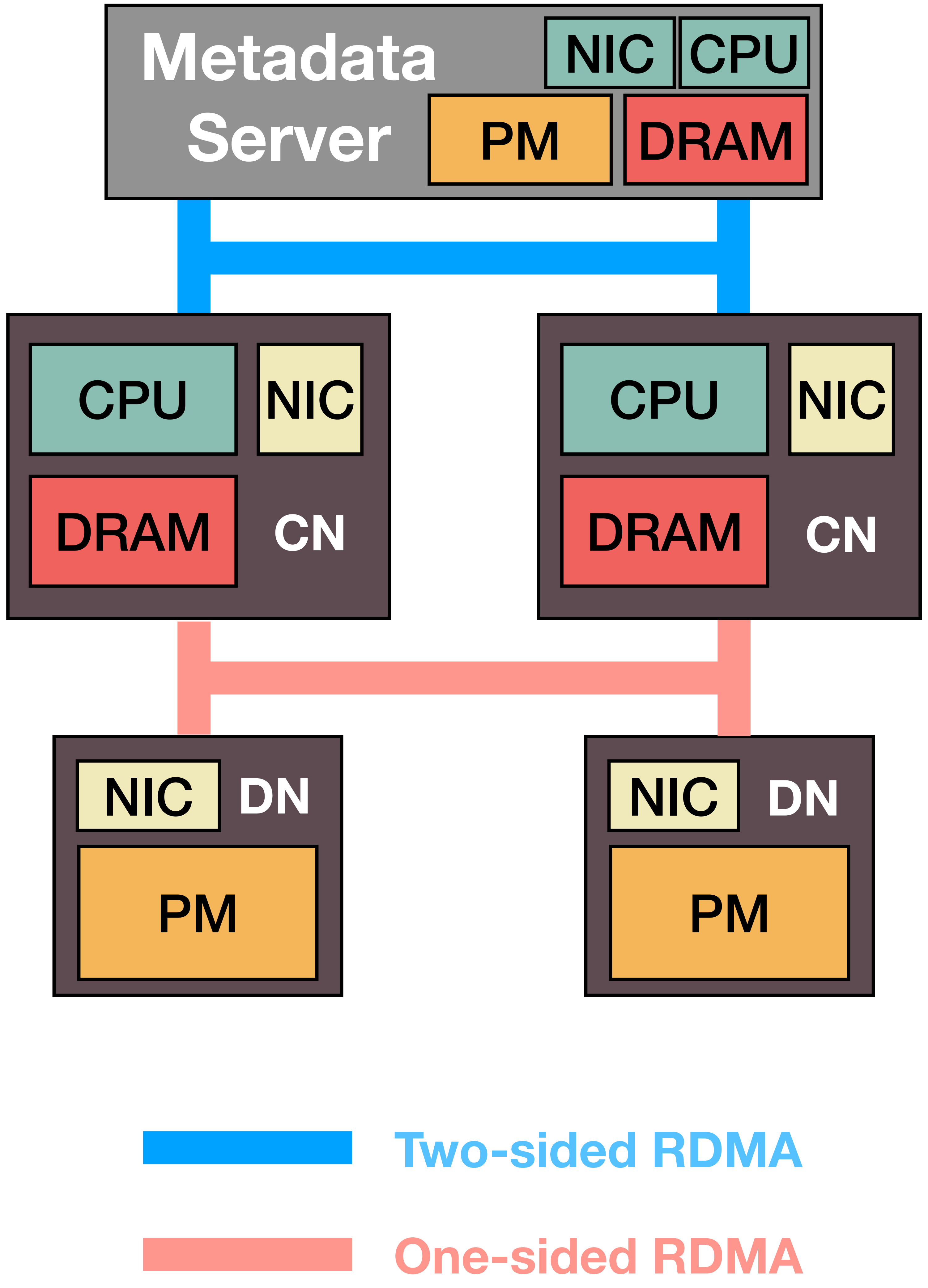
Clover: Combining Distributed and Centralized Approaches



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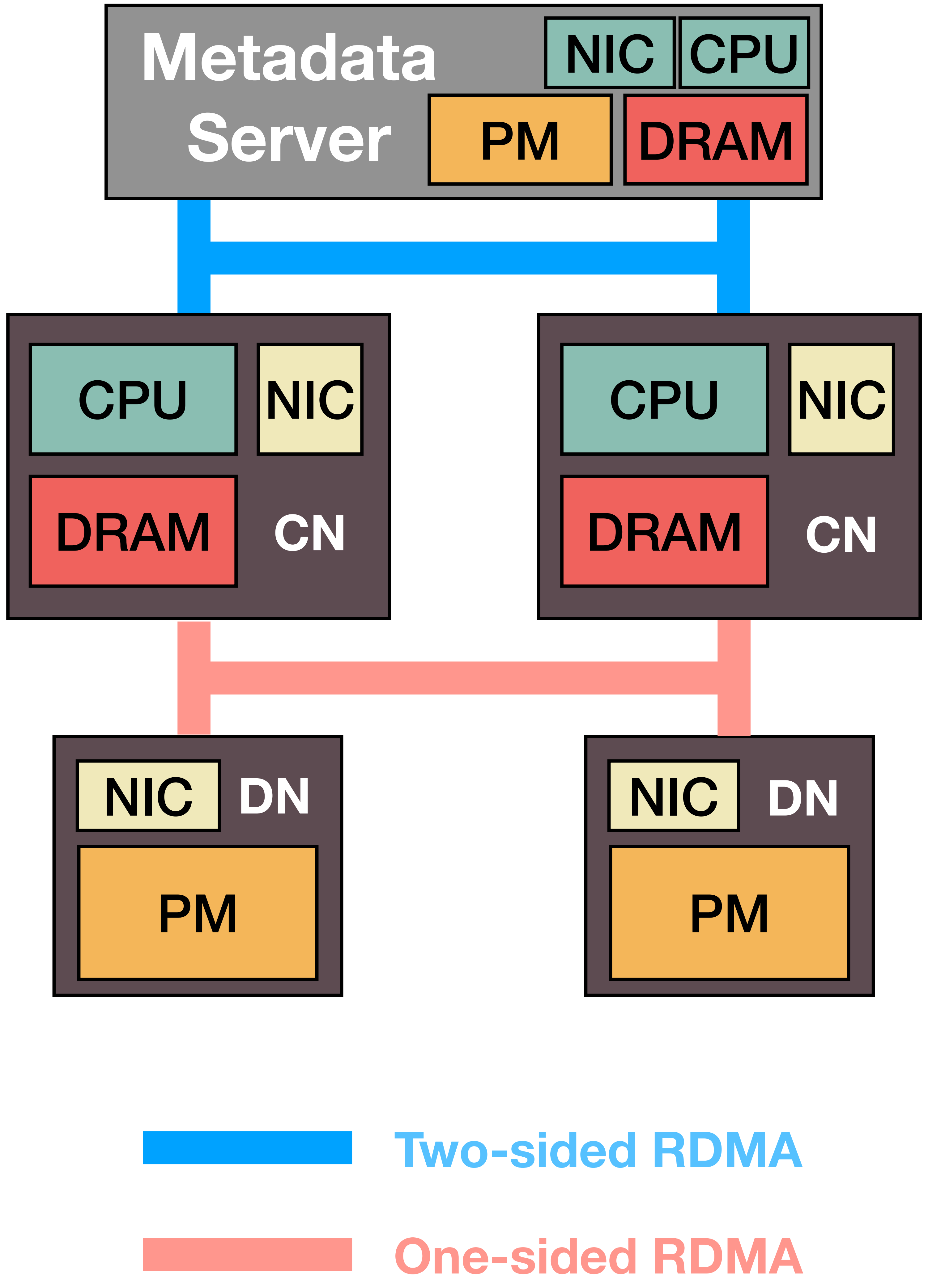

High-level idea: separate data and metadata plane

- Separate locations
- Different communication methods
- Different management strategy

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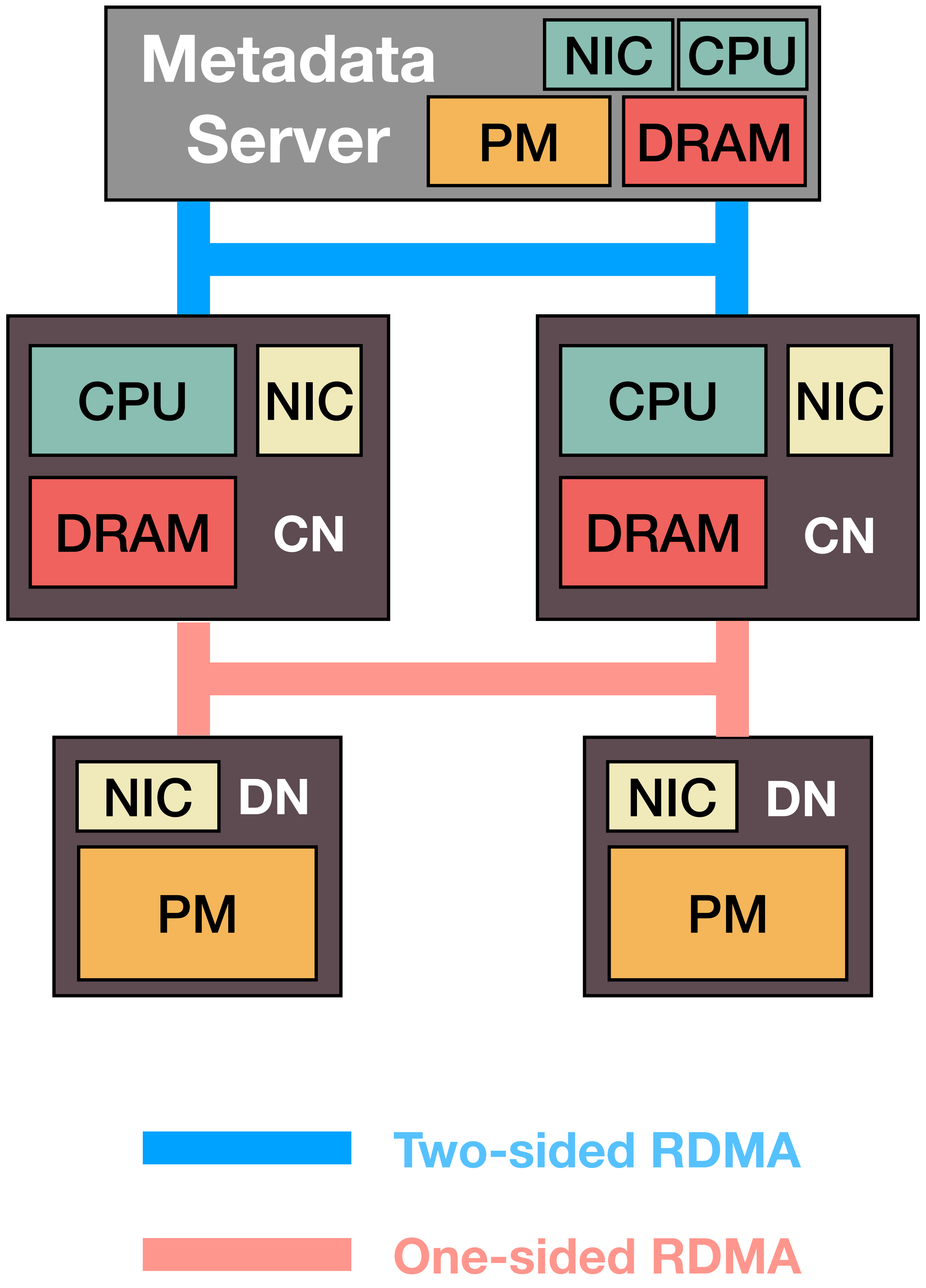

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Data Plane

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

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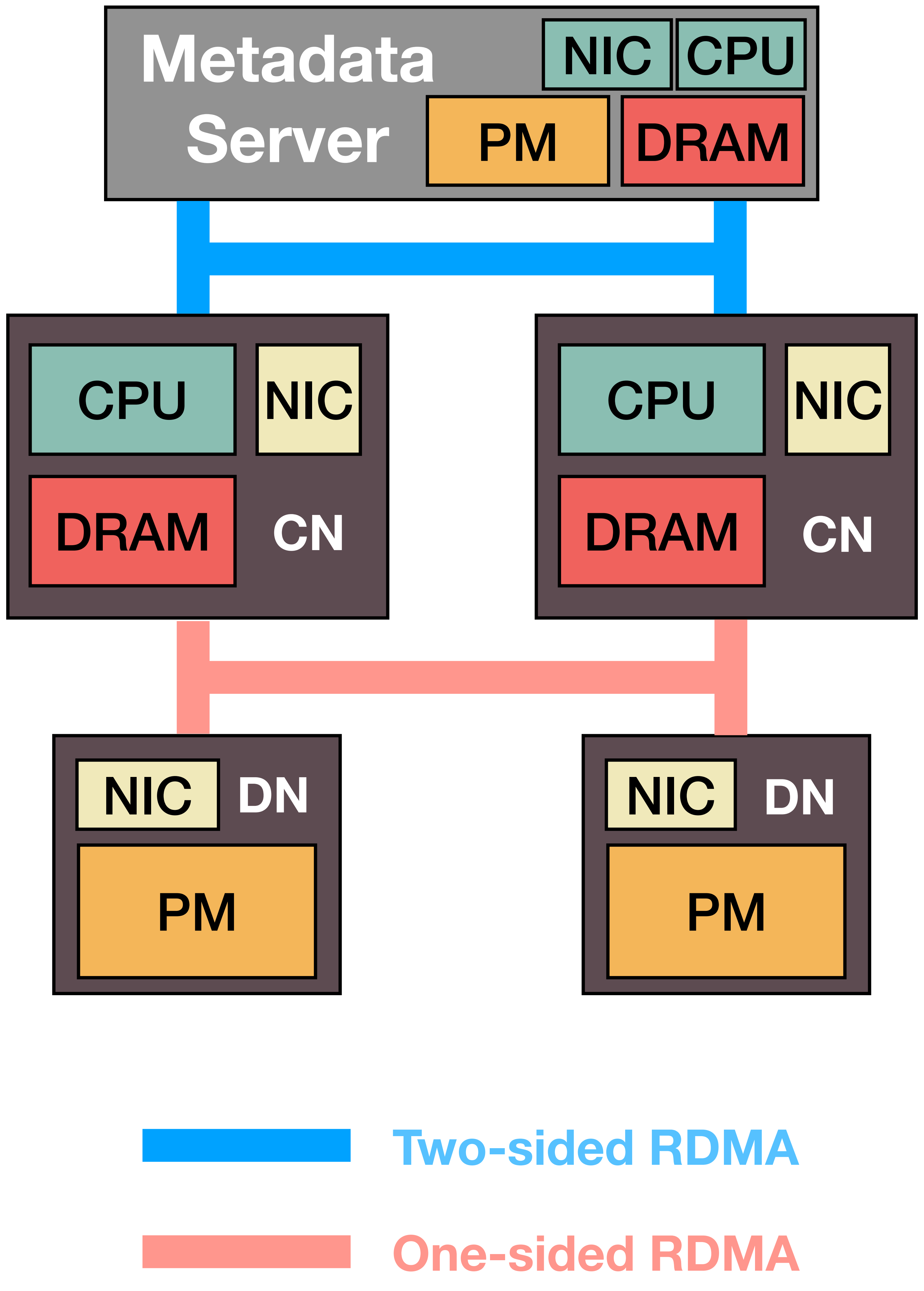

High-level idea: separate data and metadata plane

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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?

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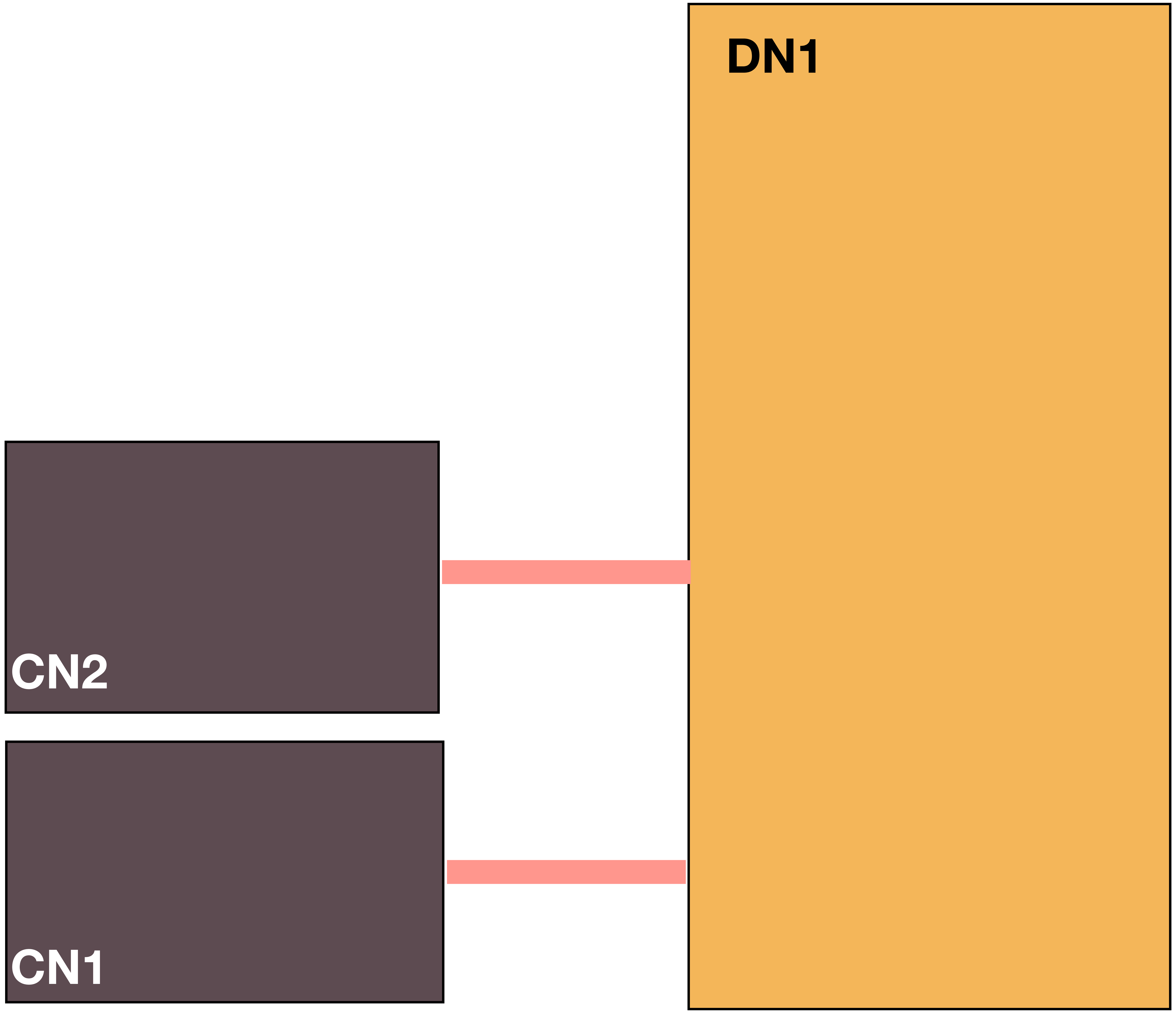
How to efficiently support concurrent data accesses from CNs to DNs?

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

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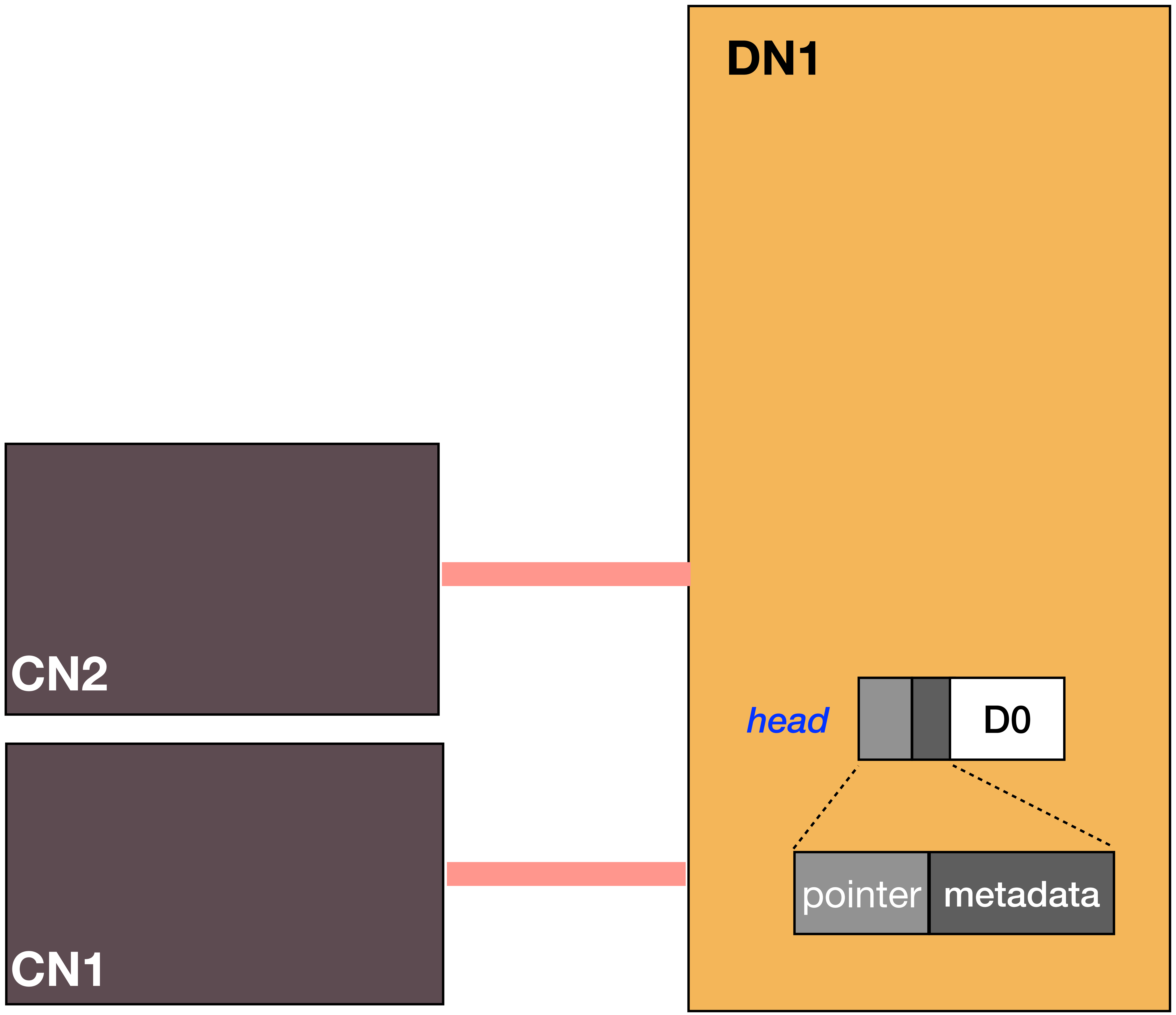

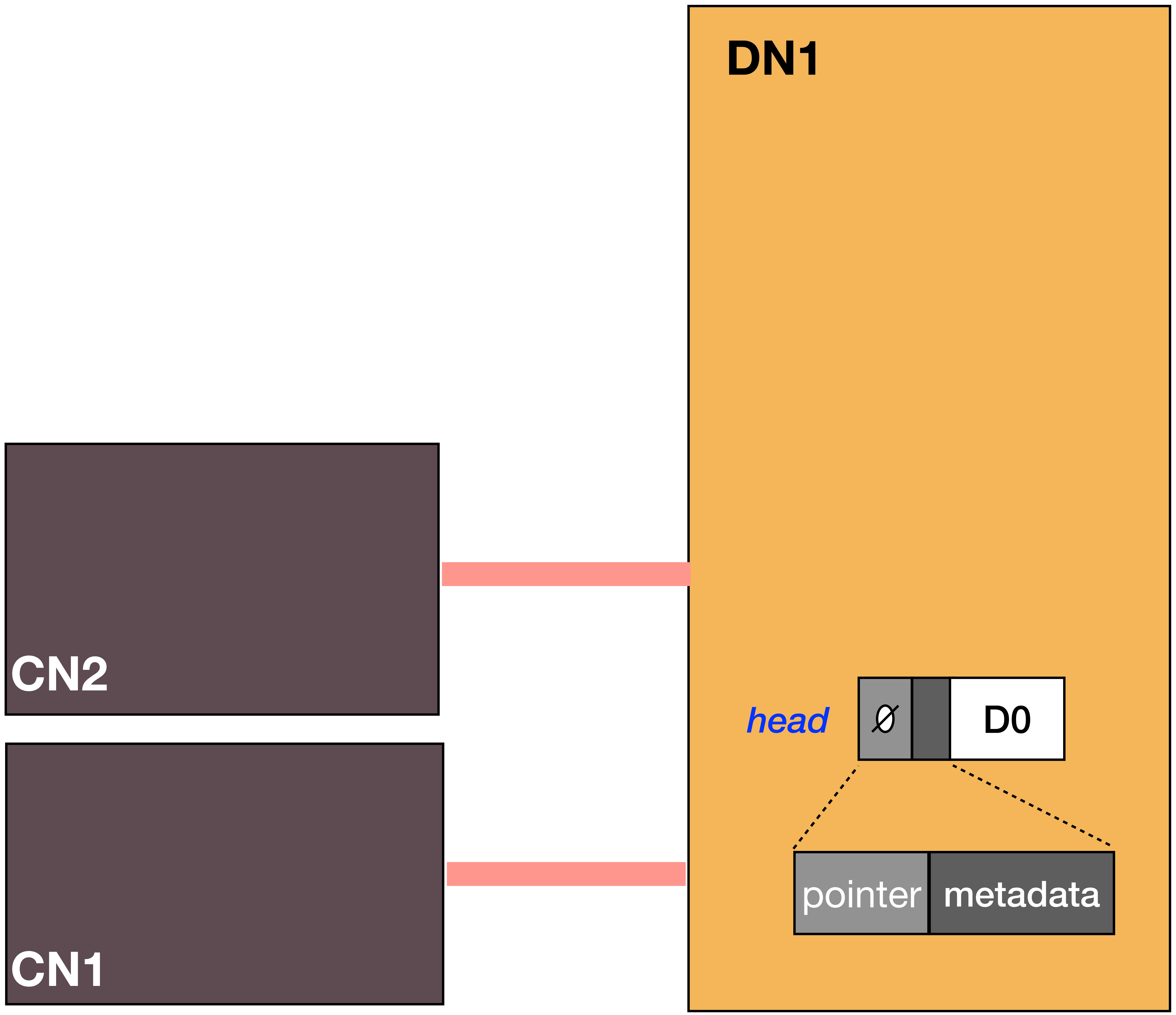

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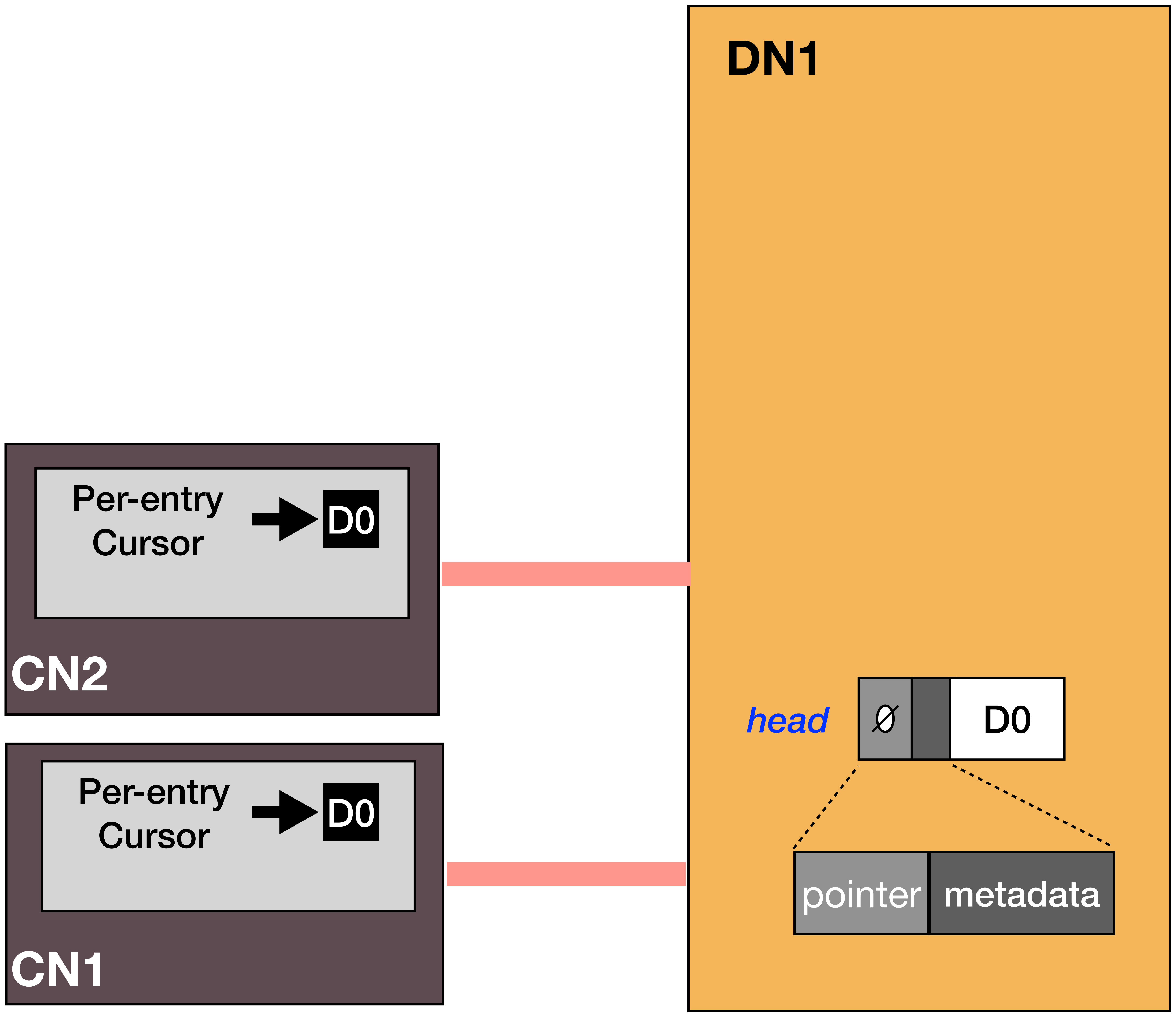

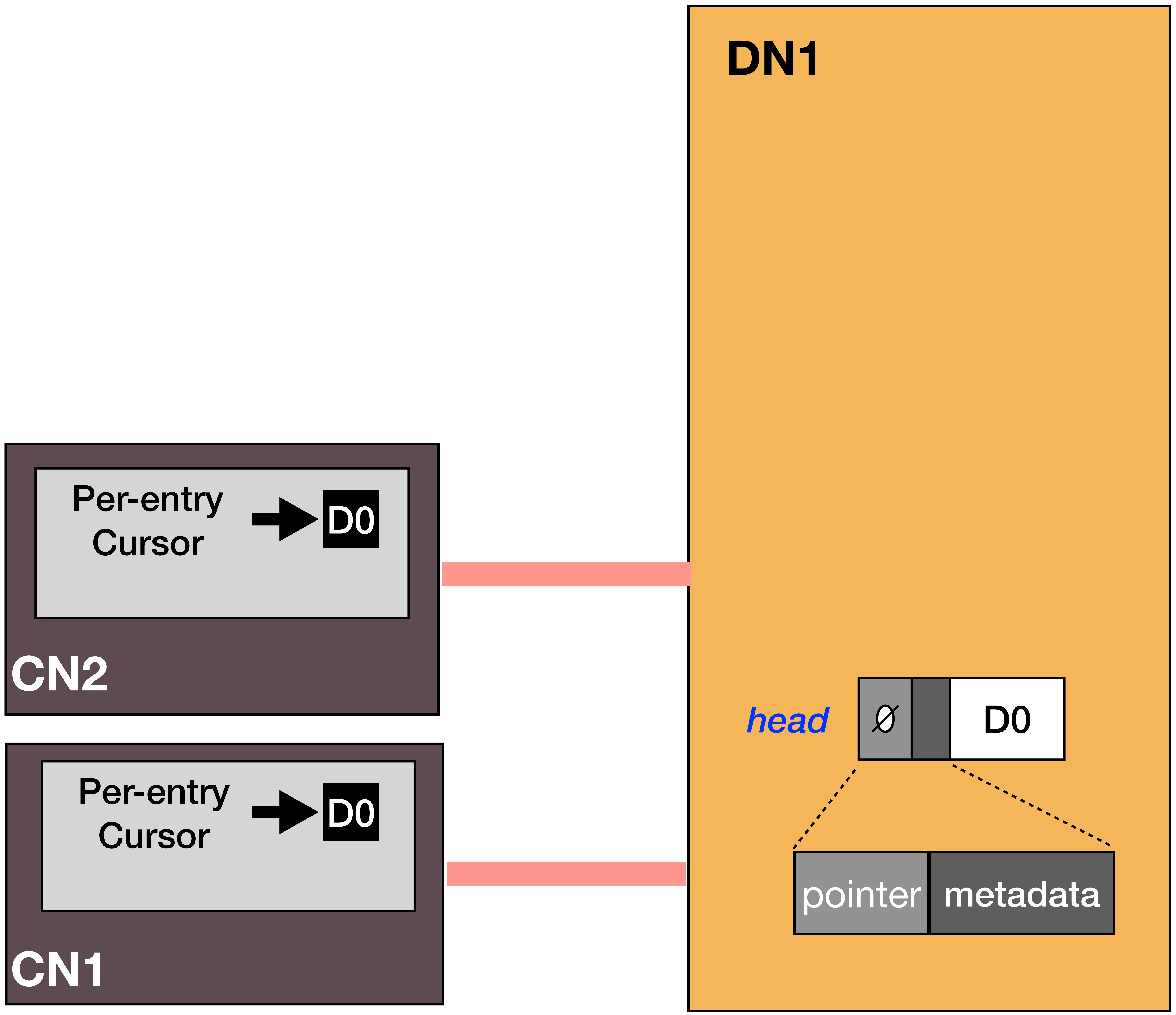

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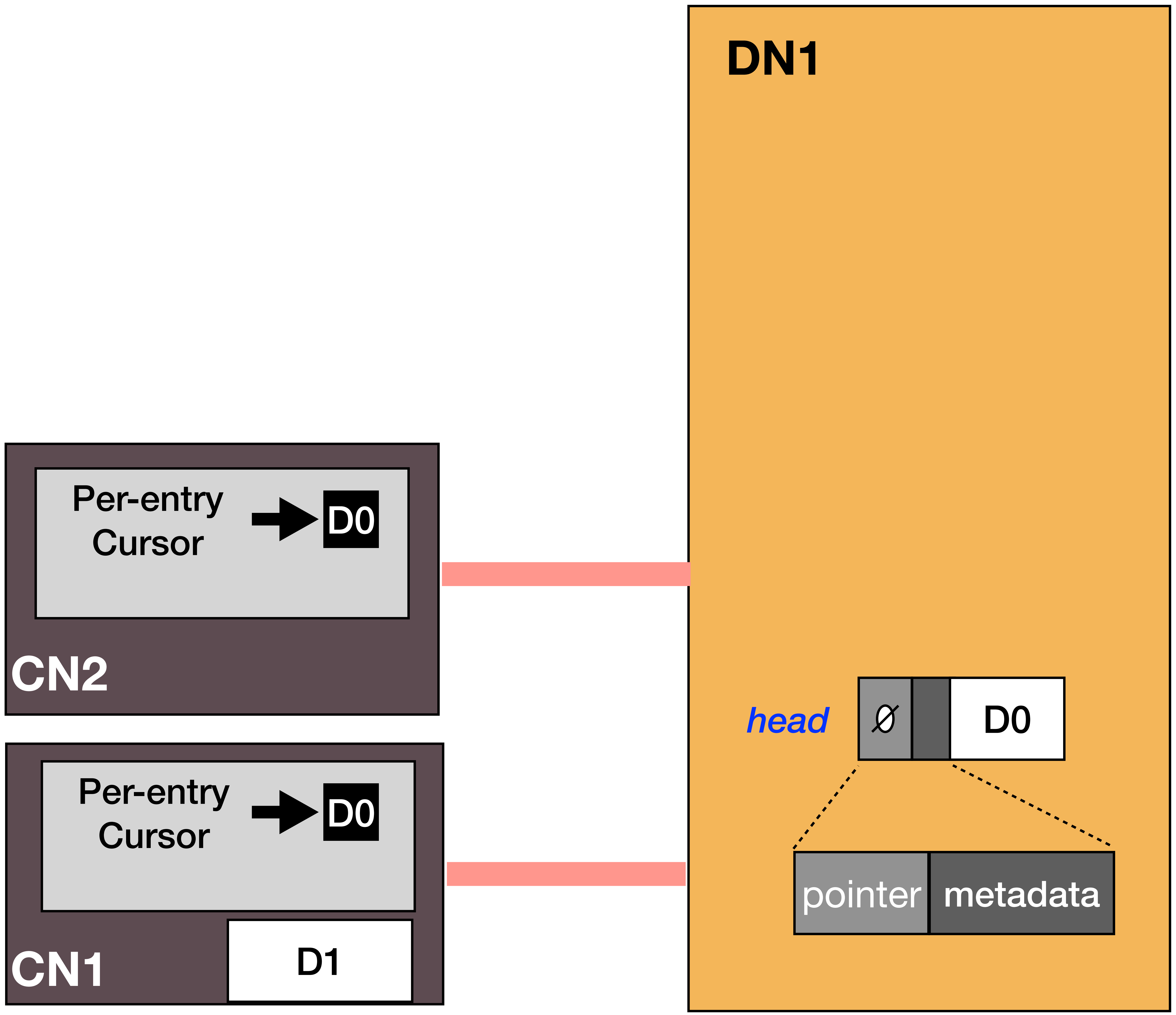

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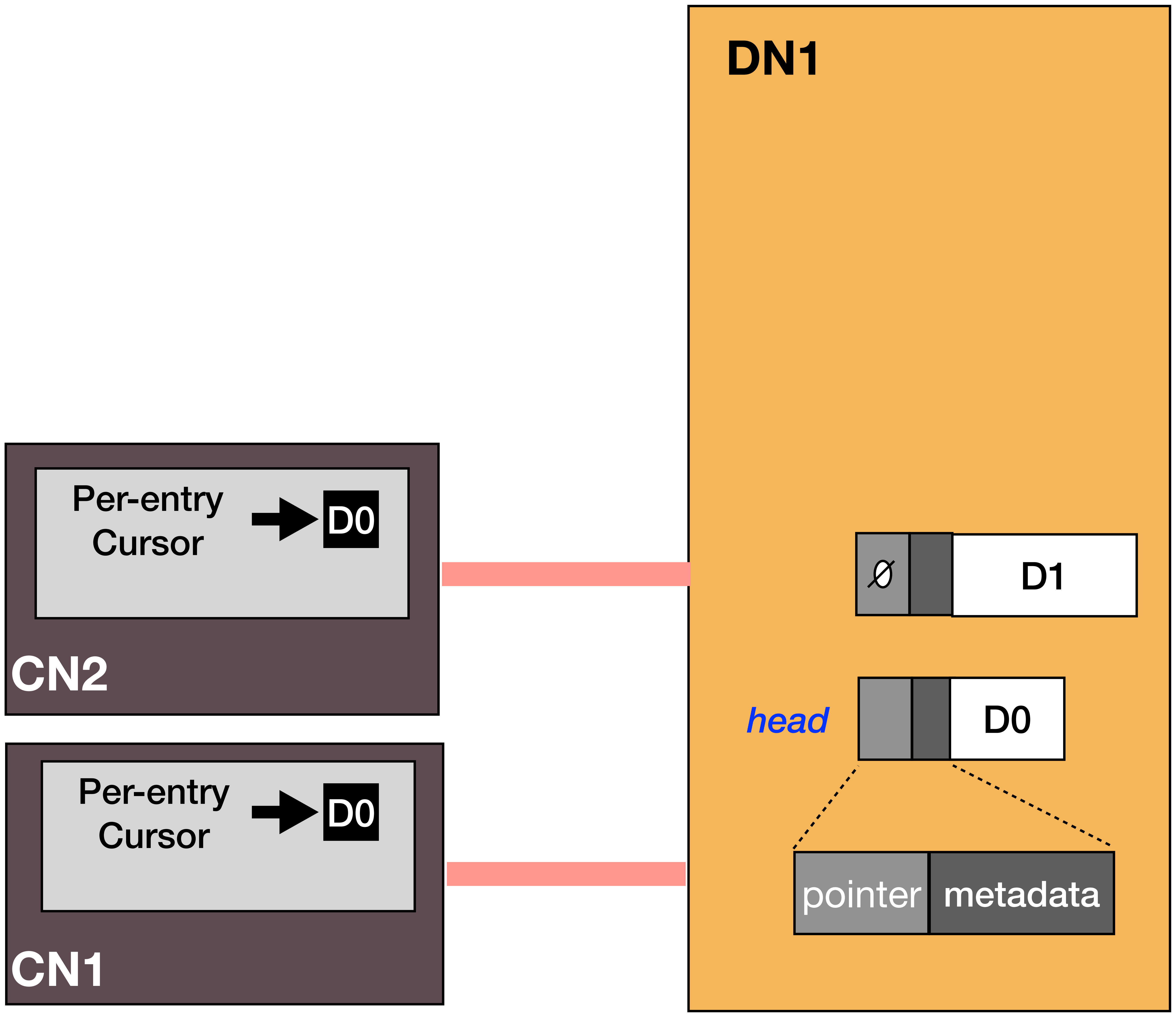

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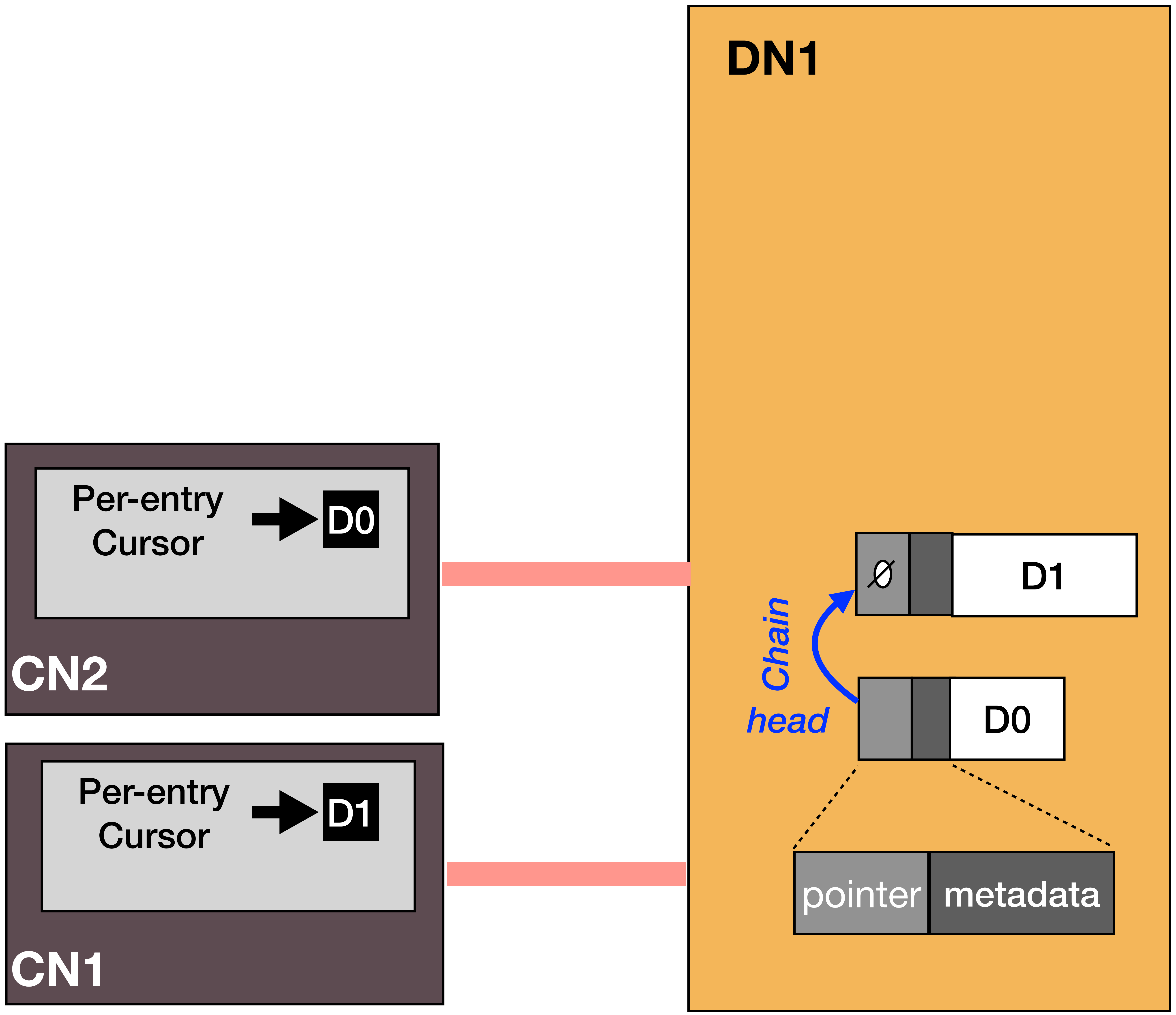

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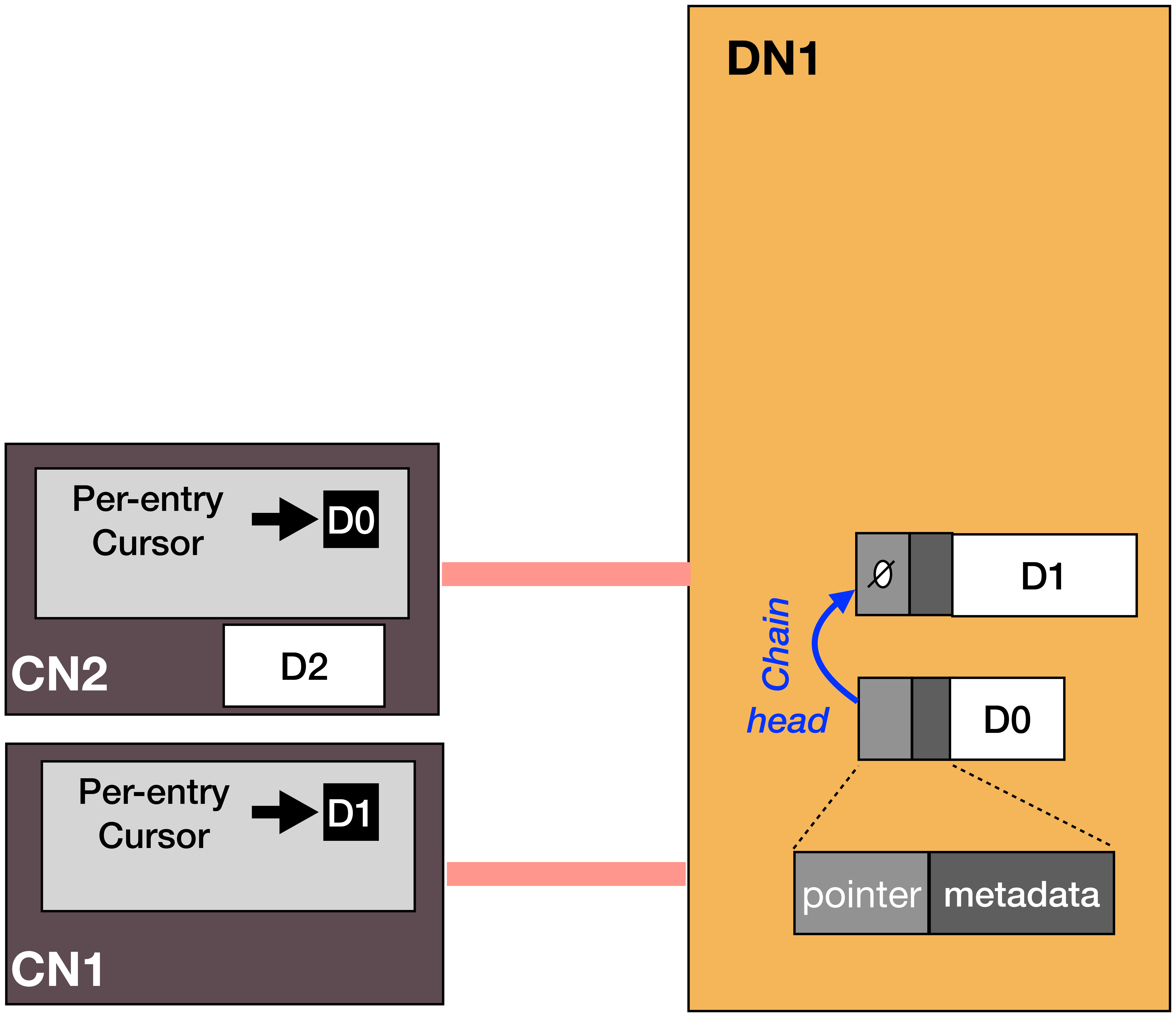

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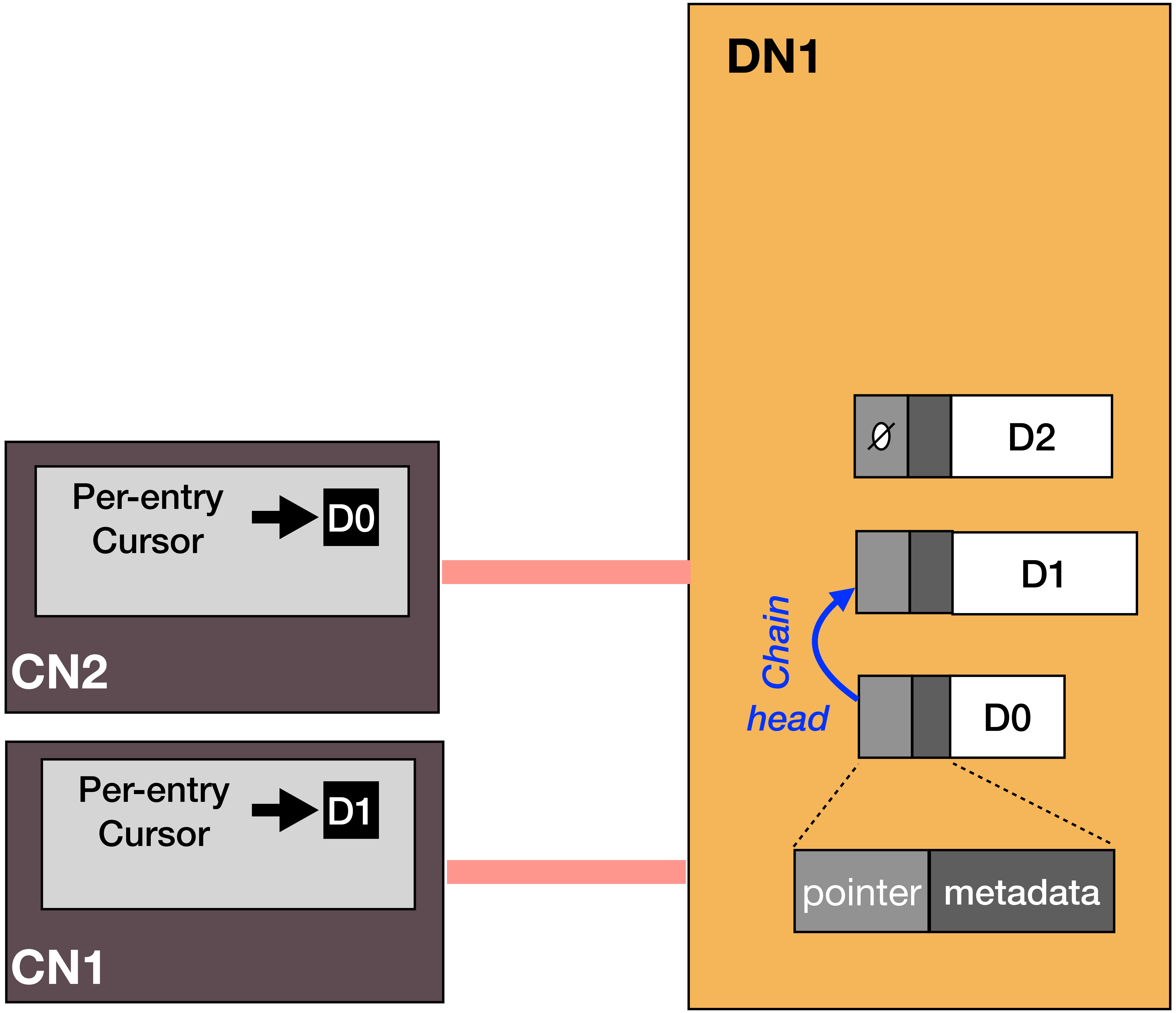

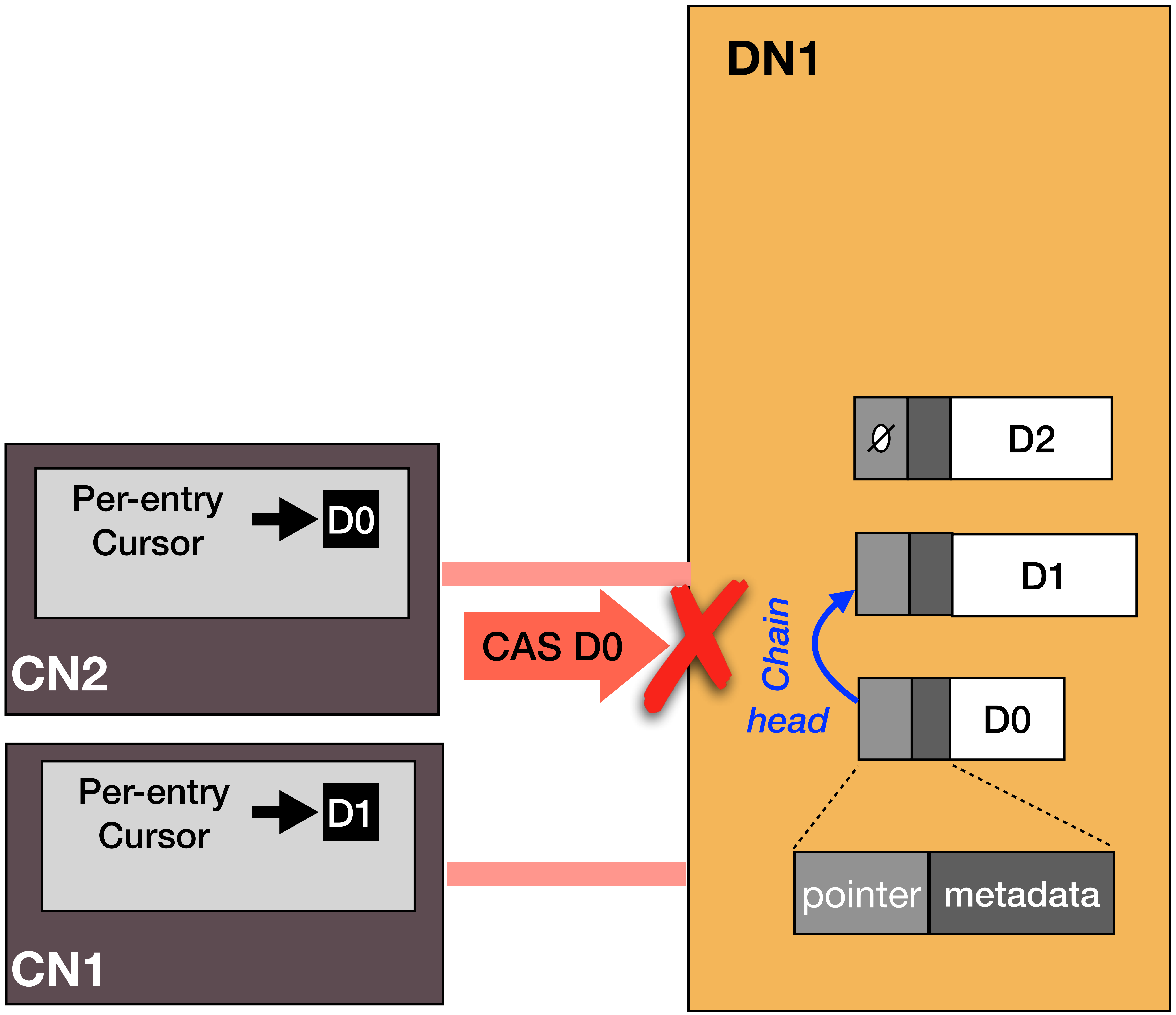

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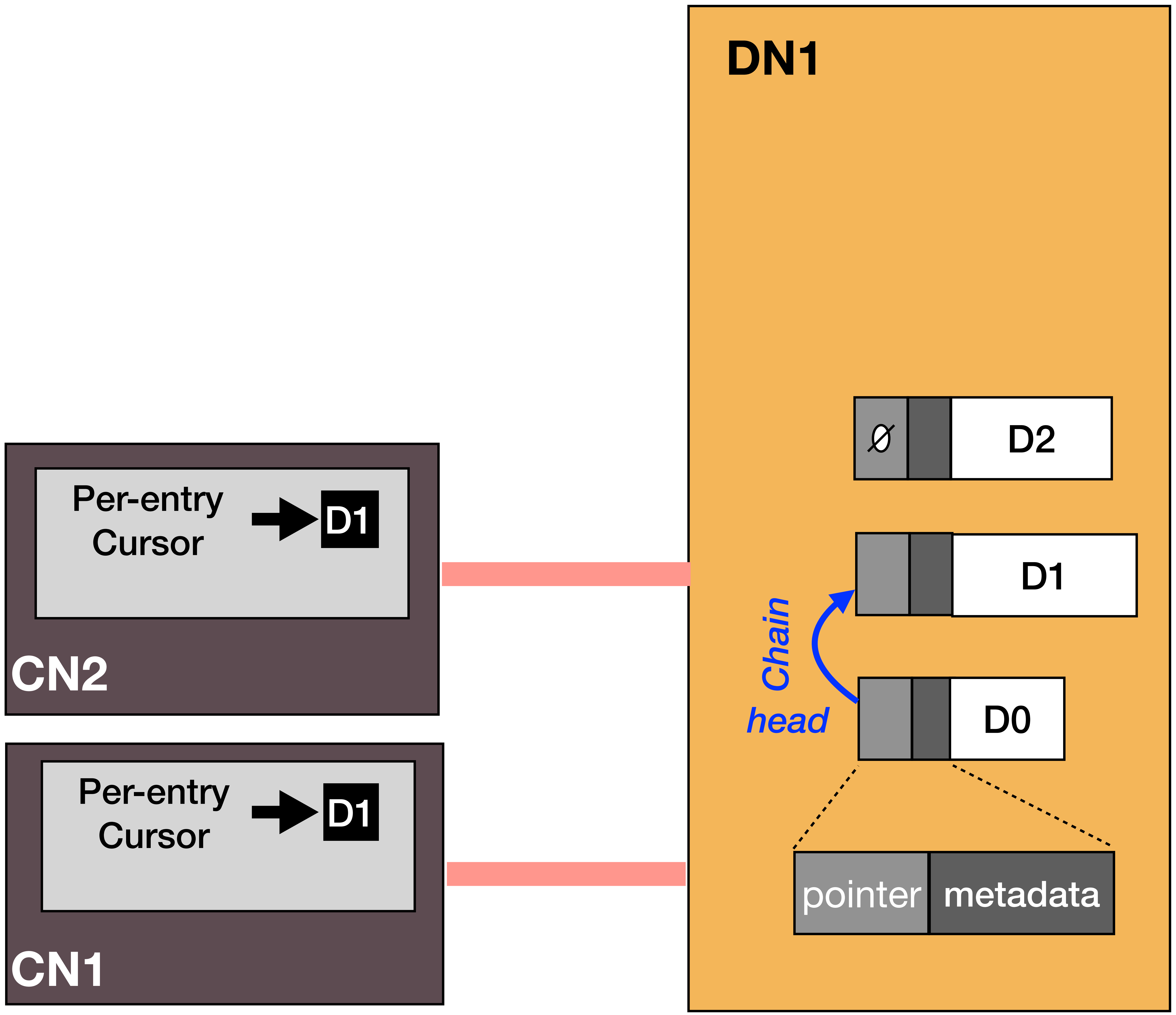

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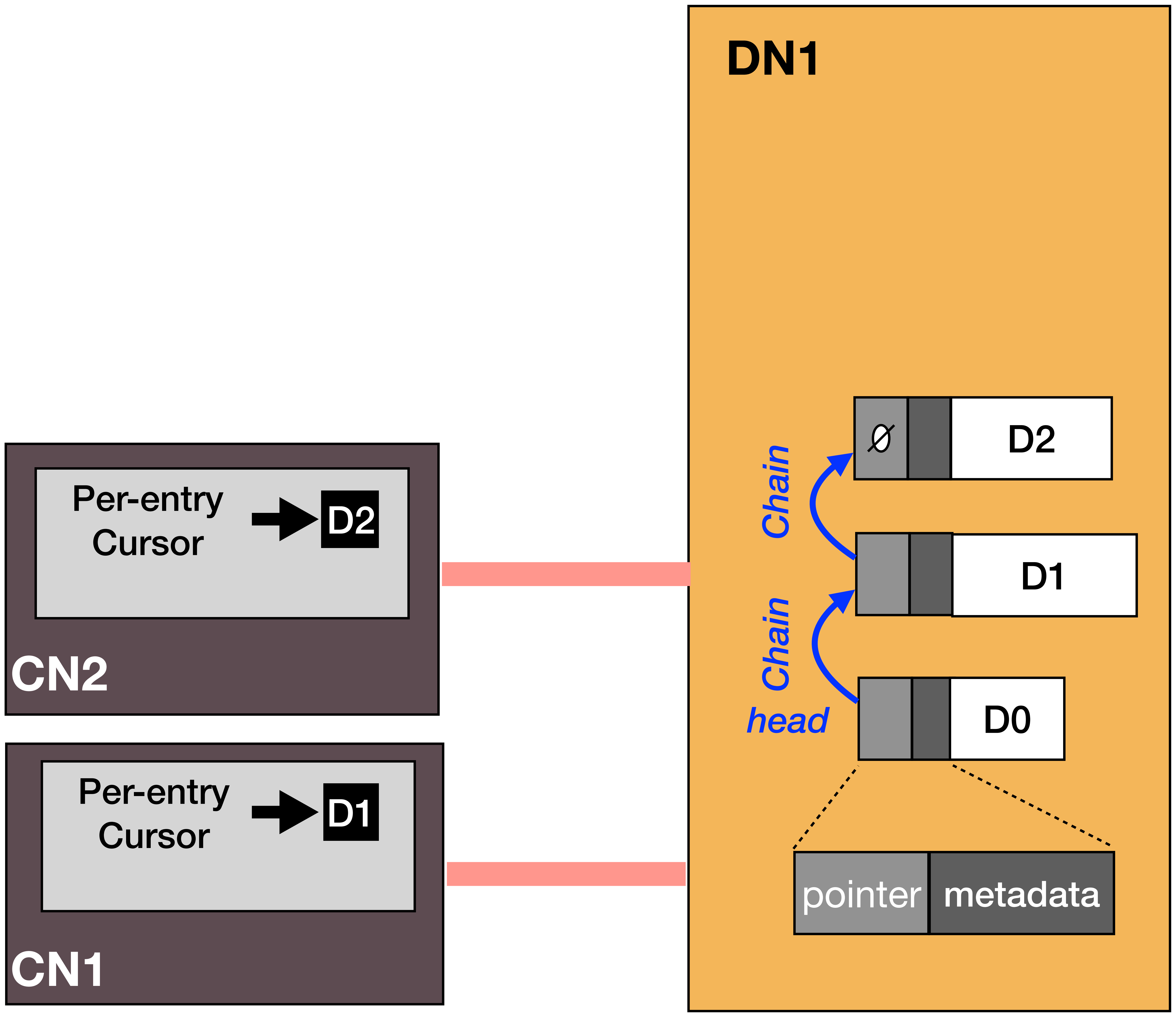

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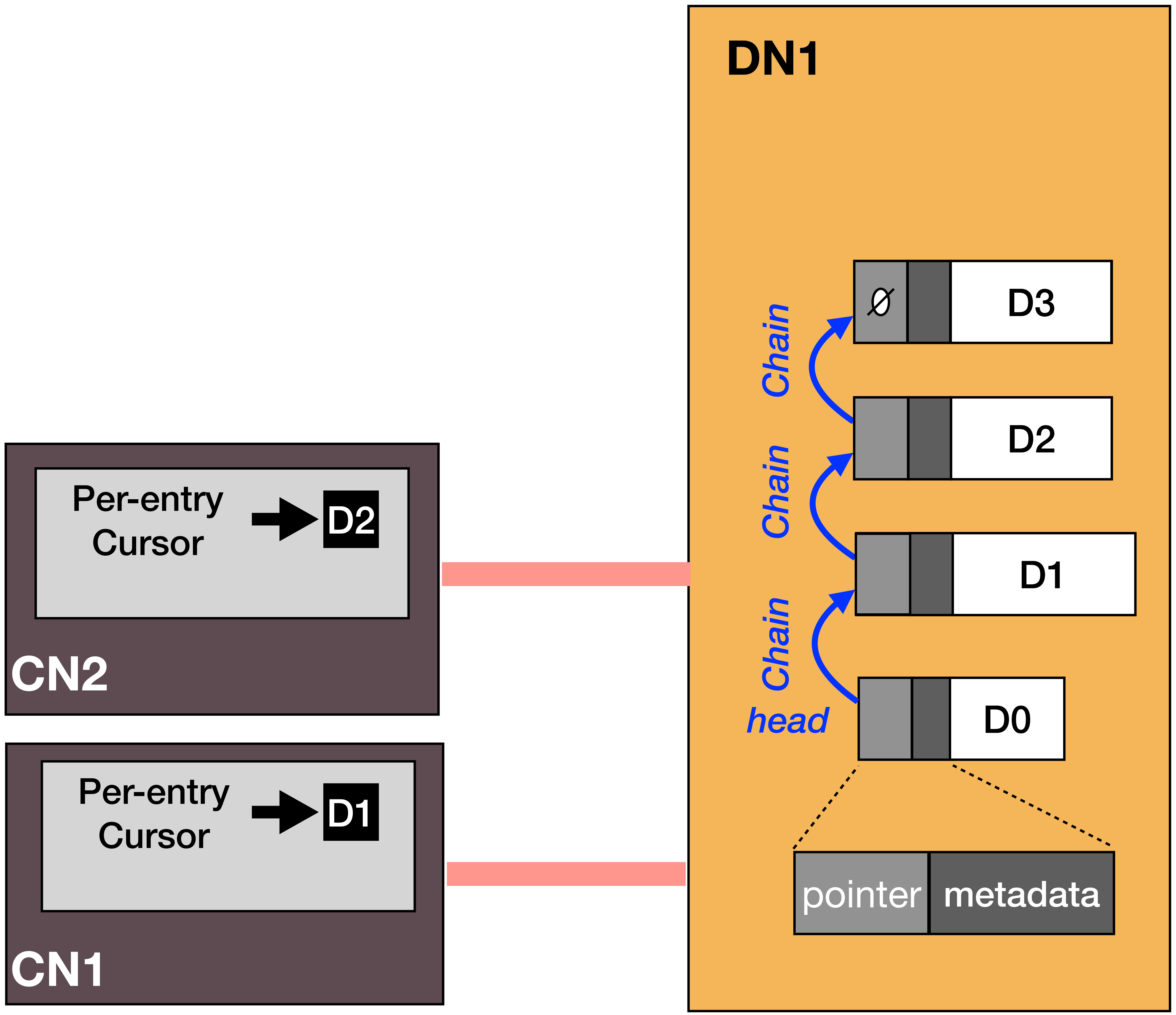

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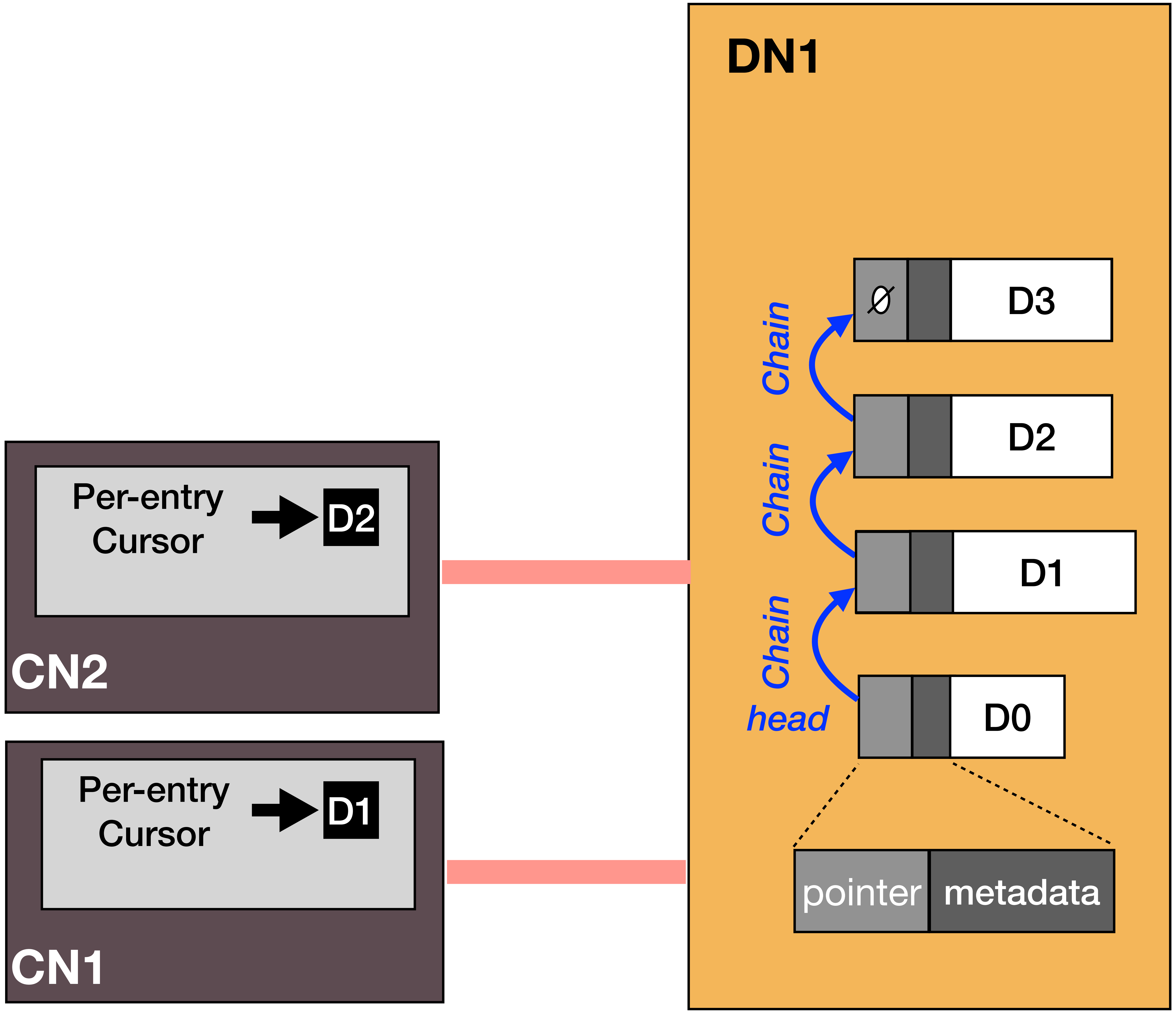

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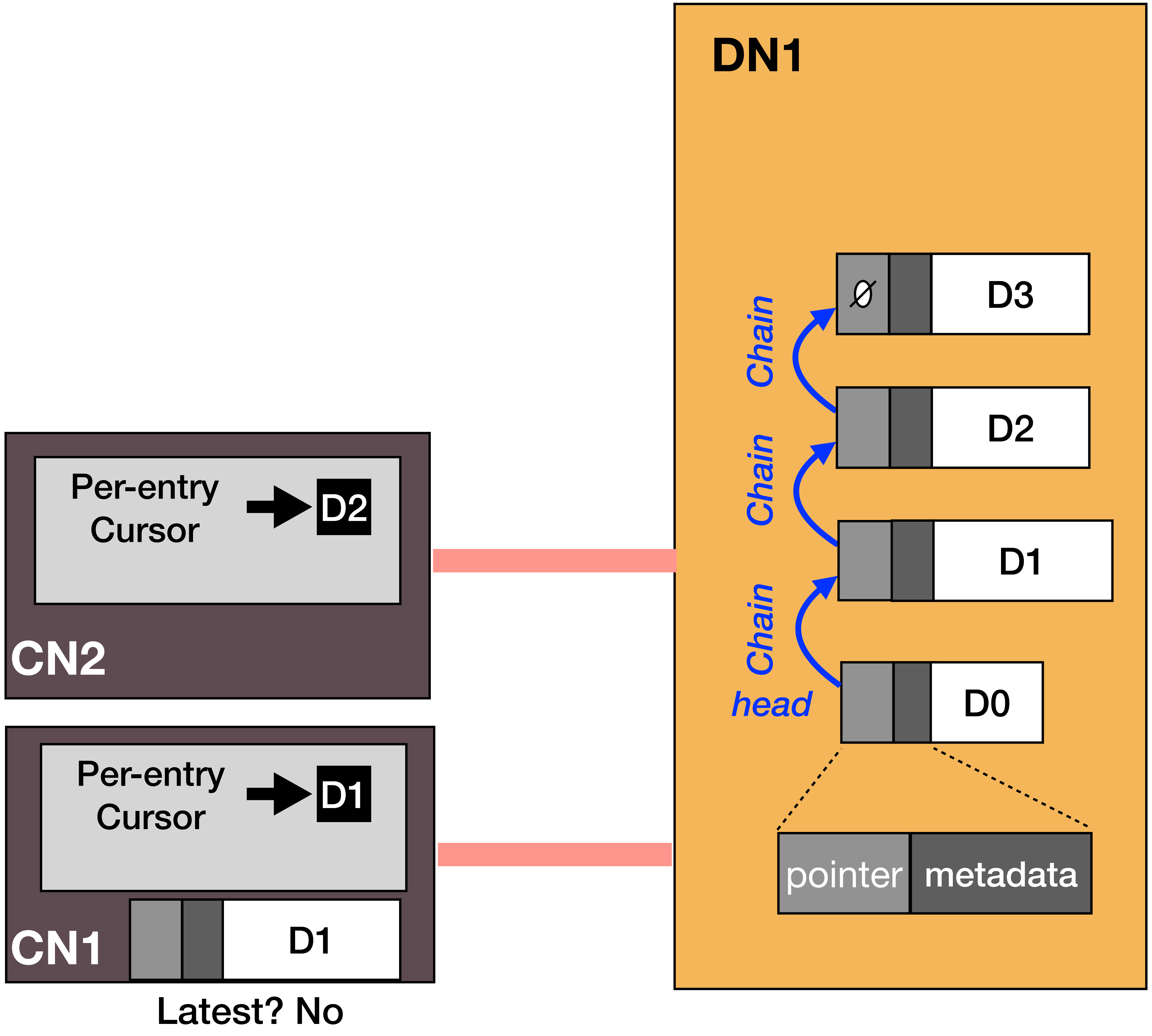

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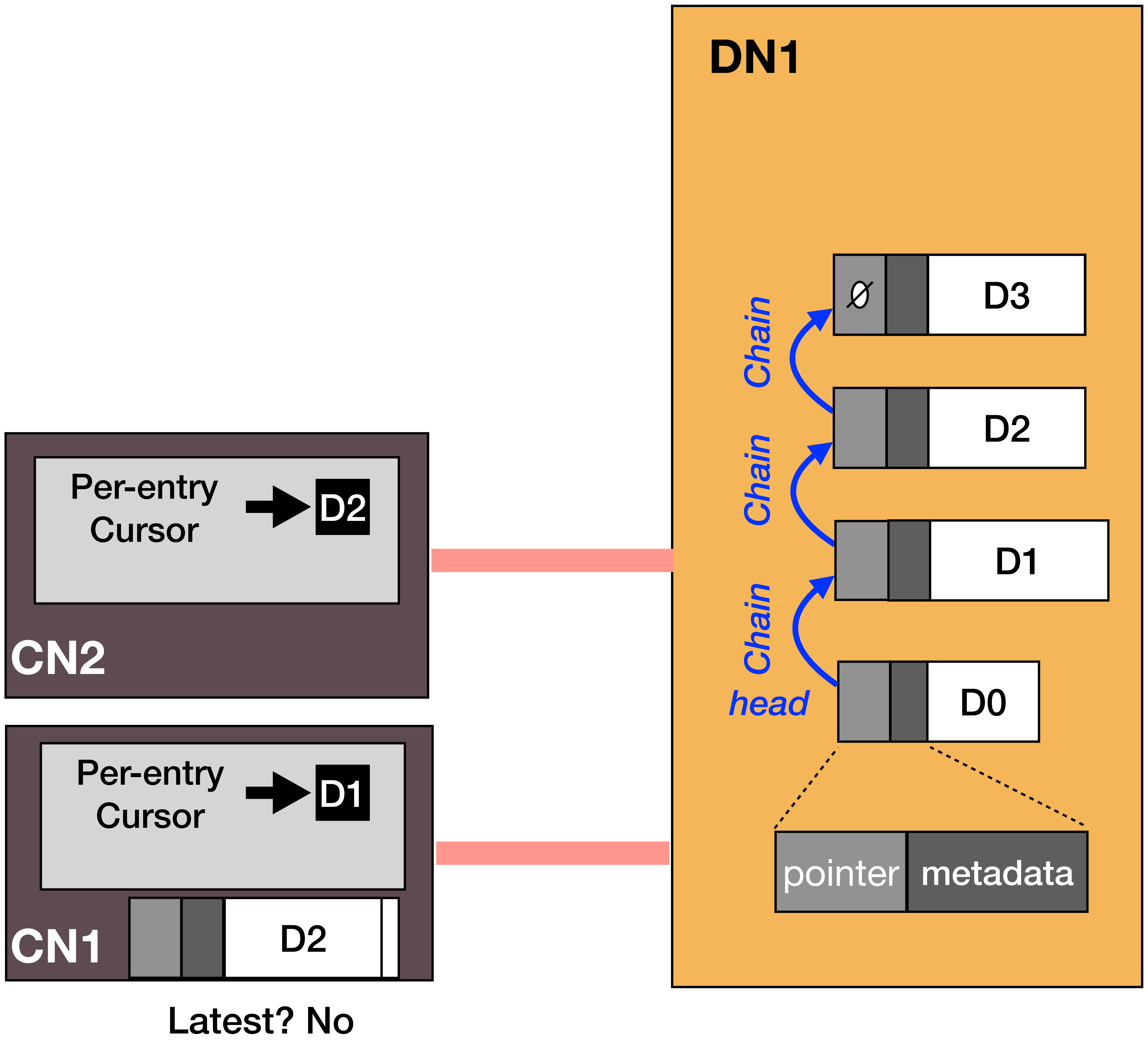

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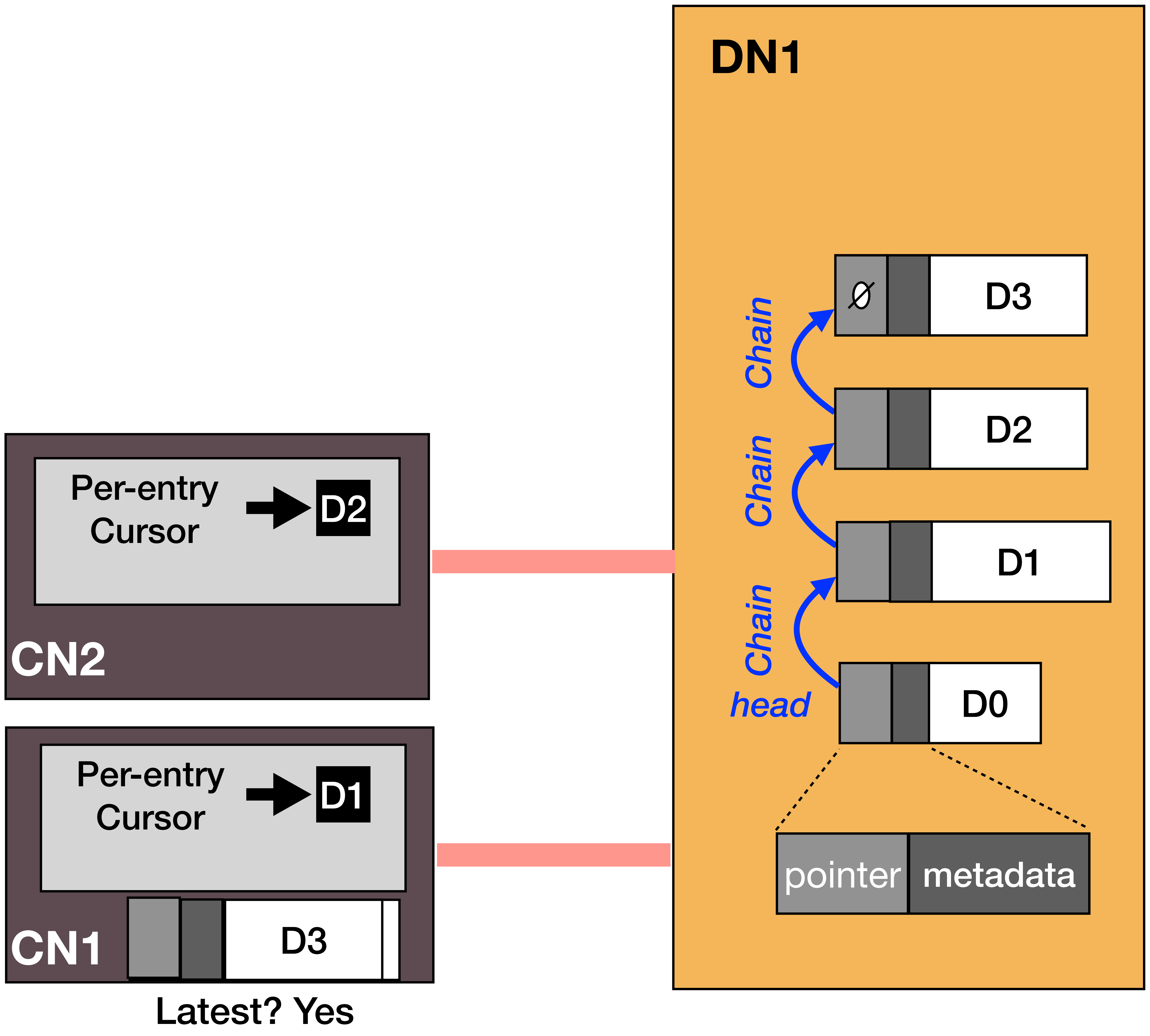

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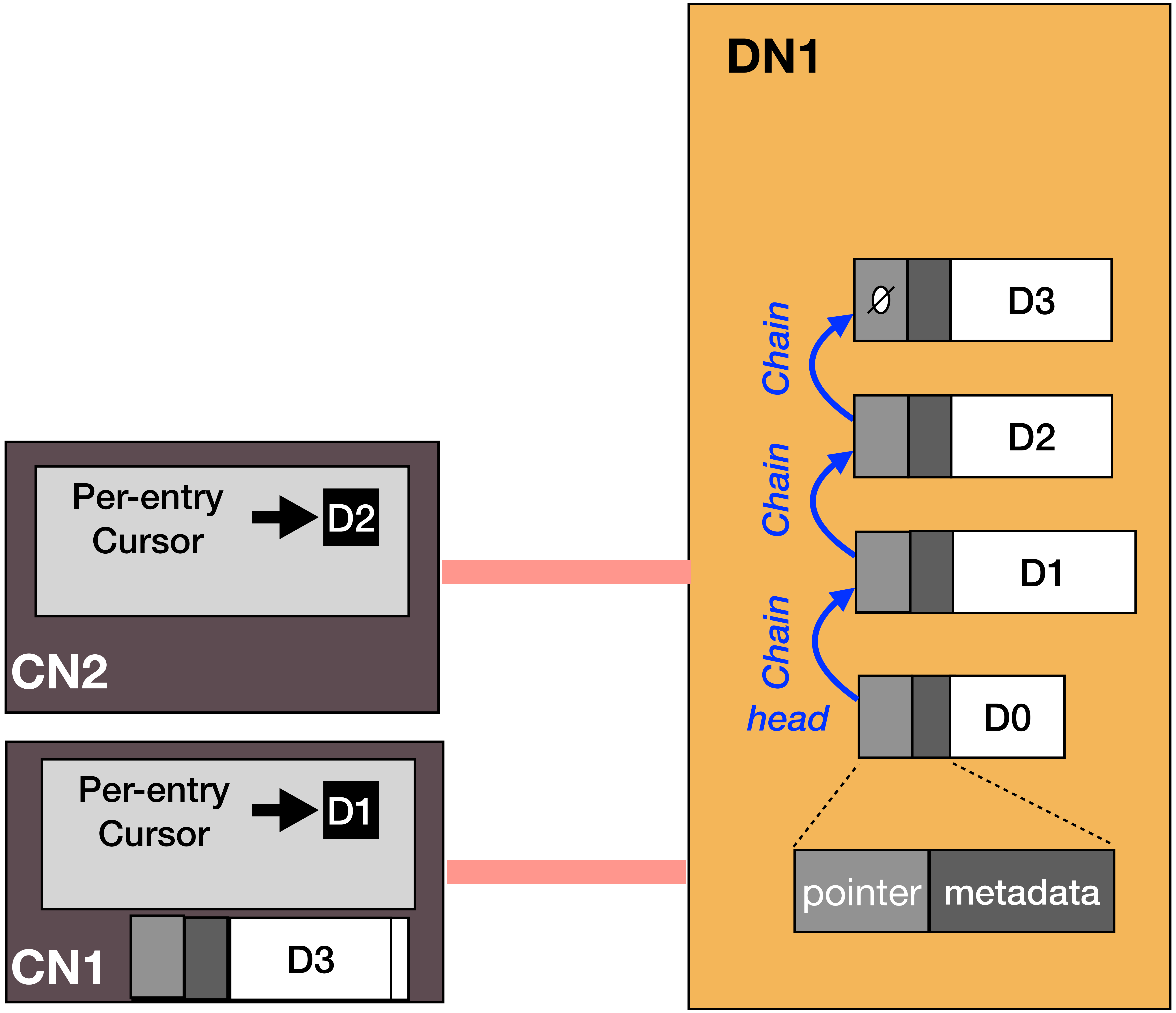

Latest? Yes

3 RTTs to finish a KV READ!

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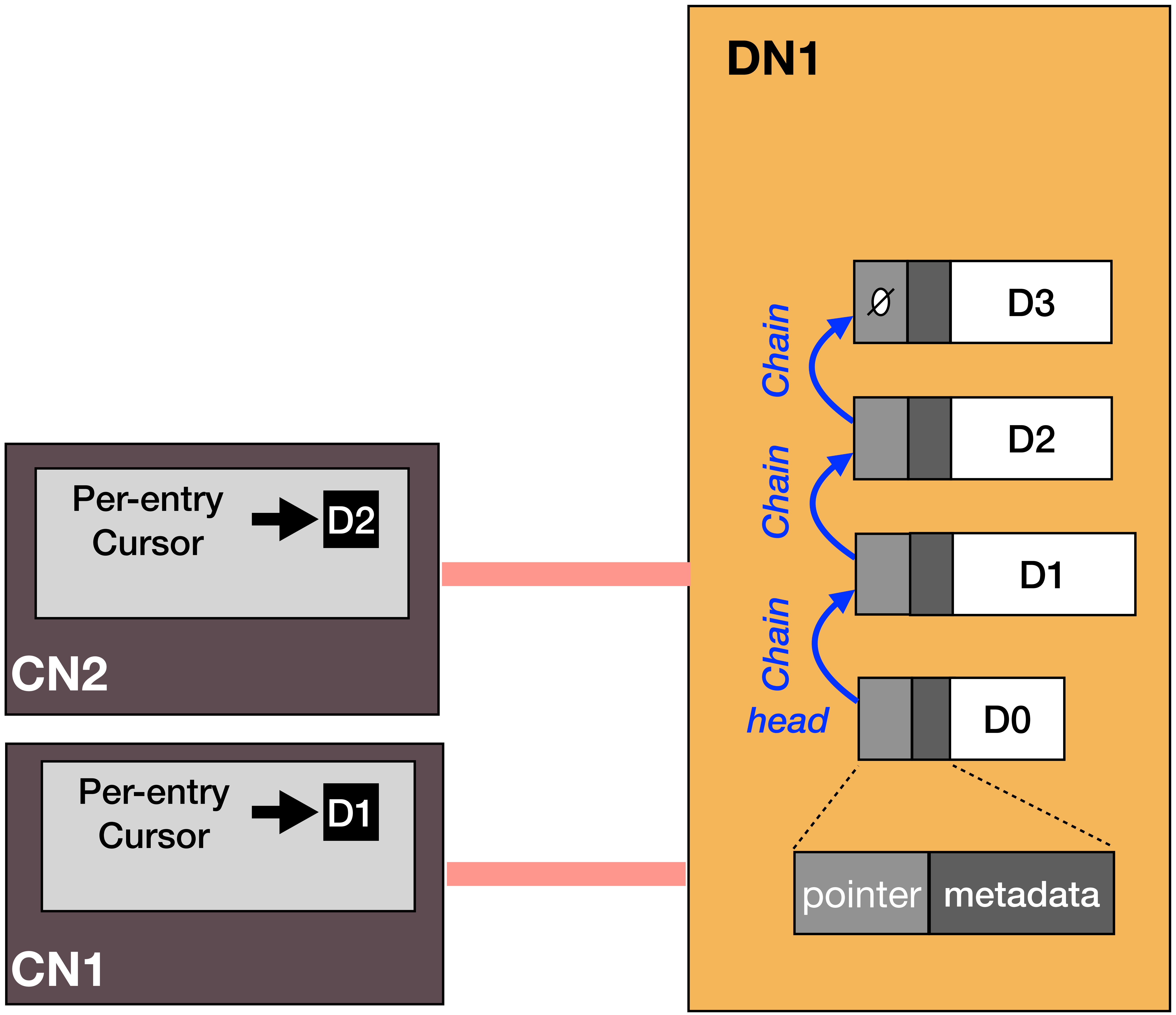

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Uses a shortcut to avoid long chain walk
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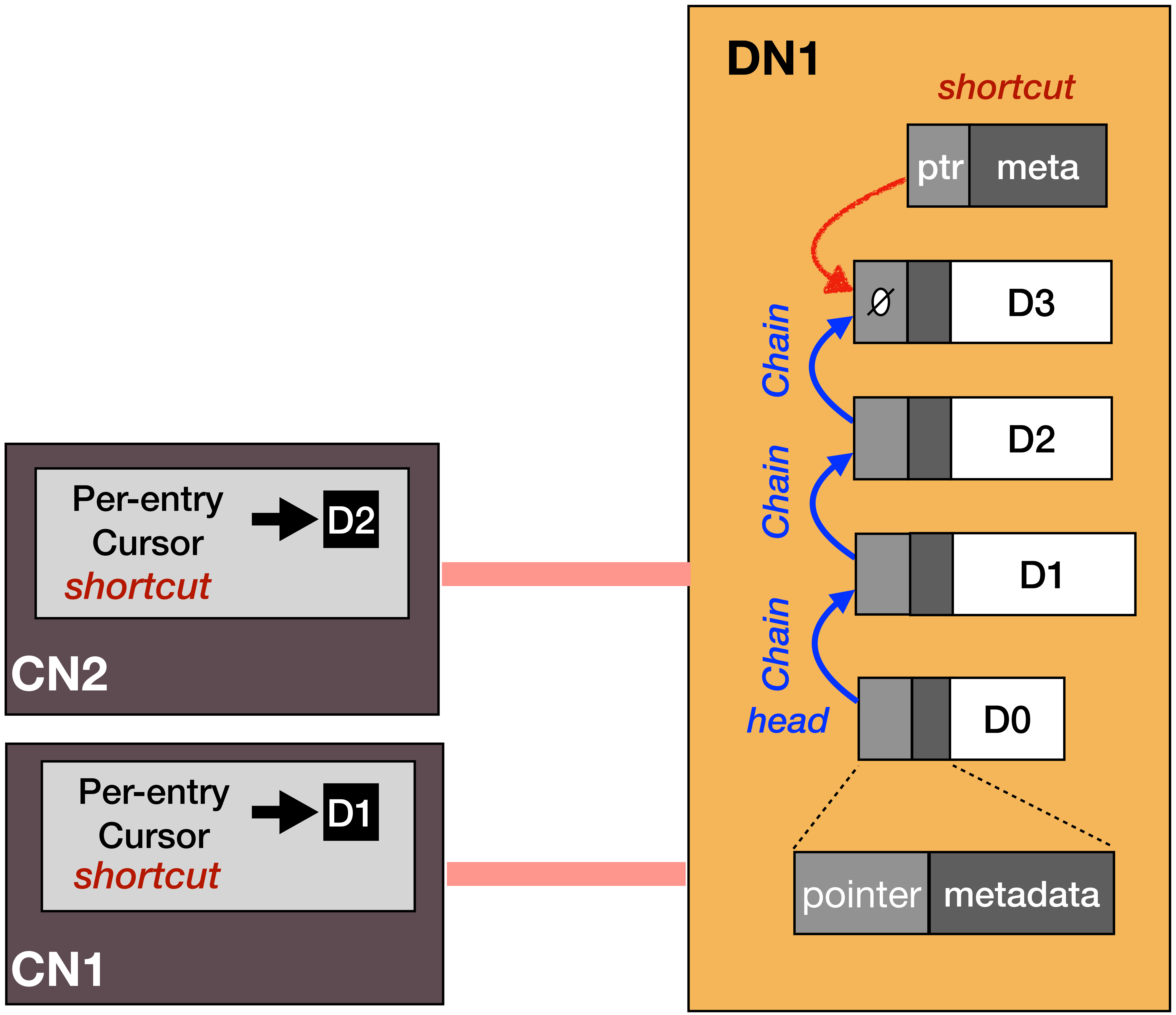

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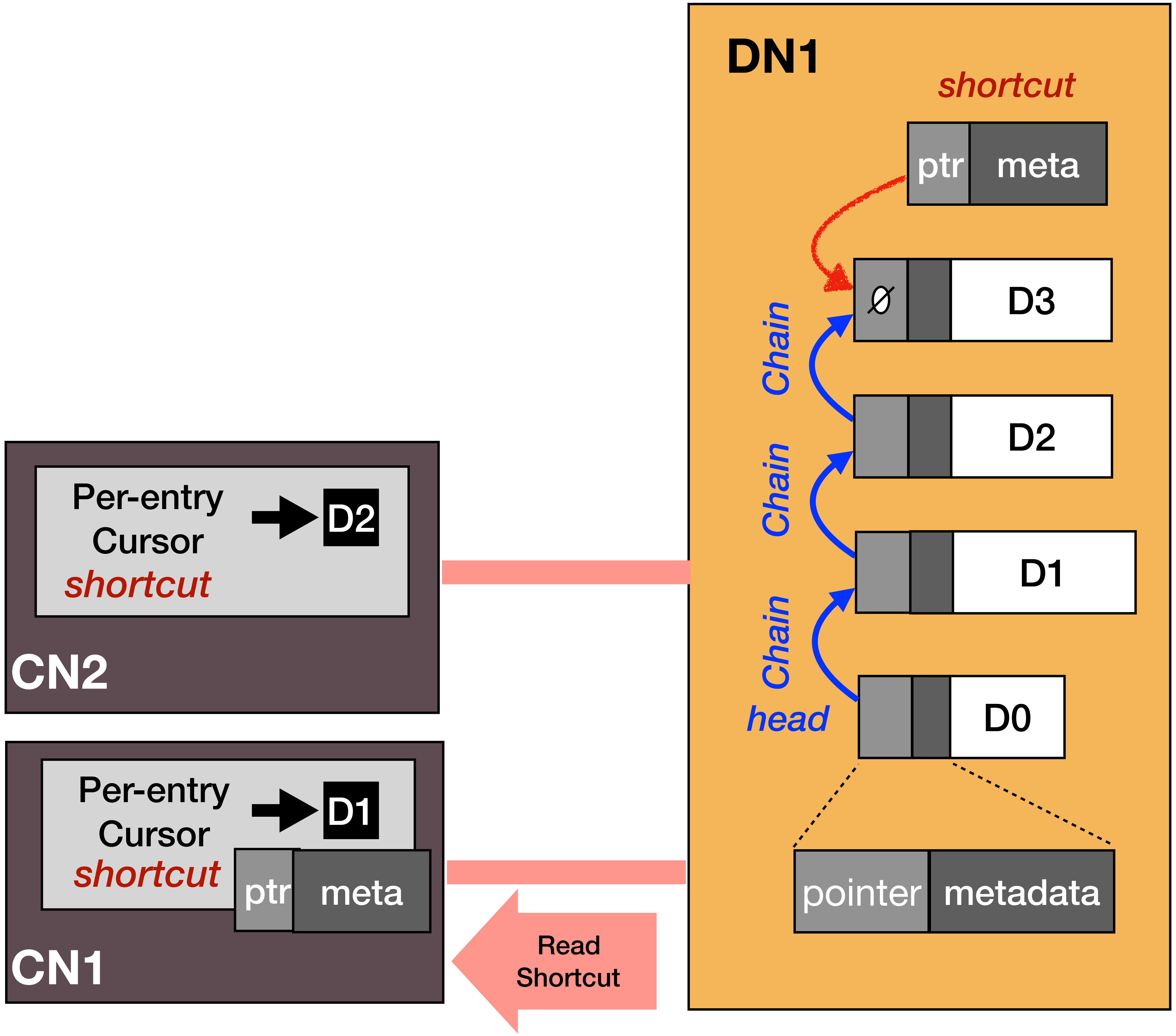

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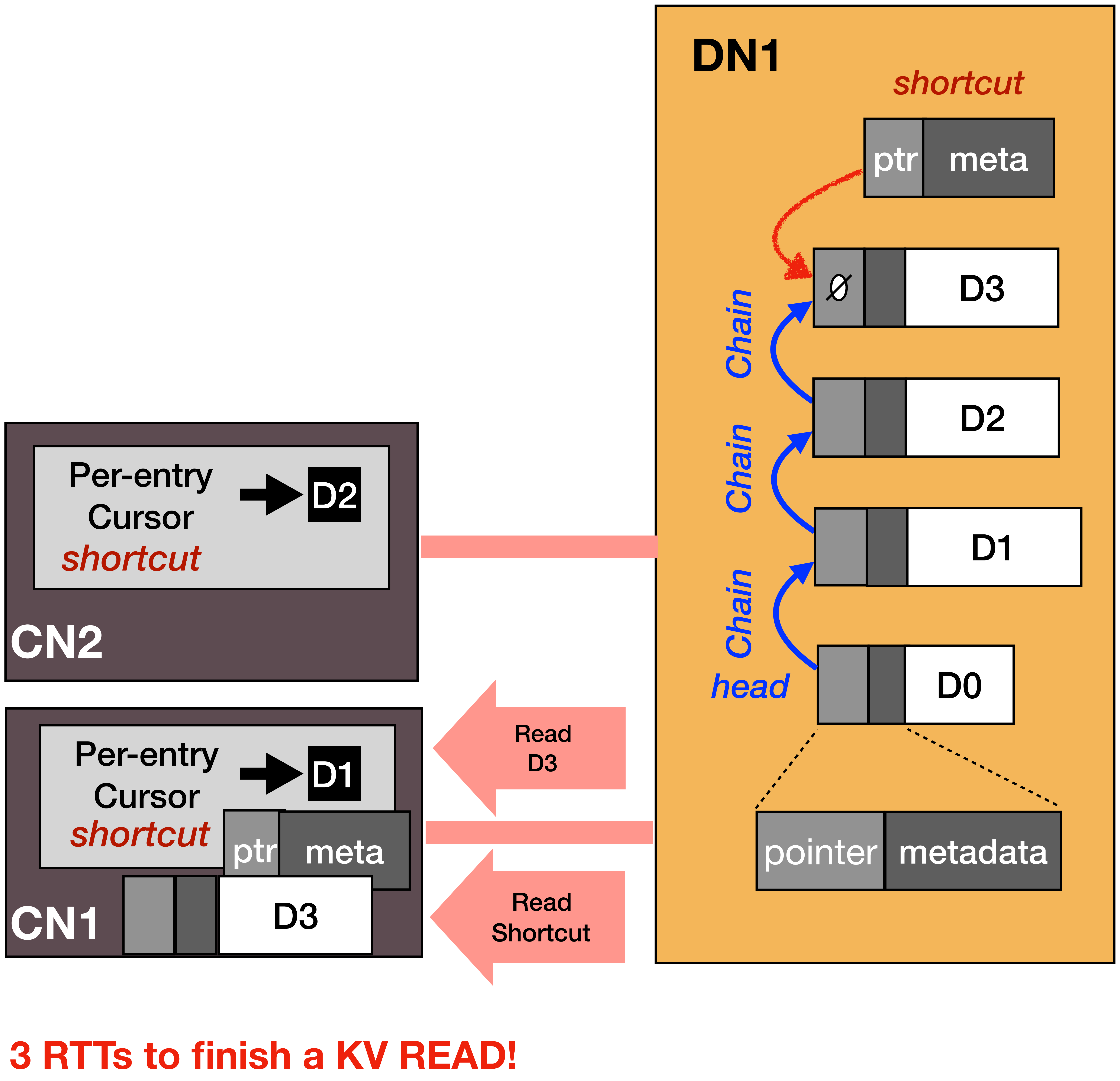

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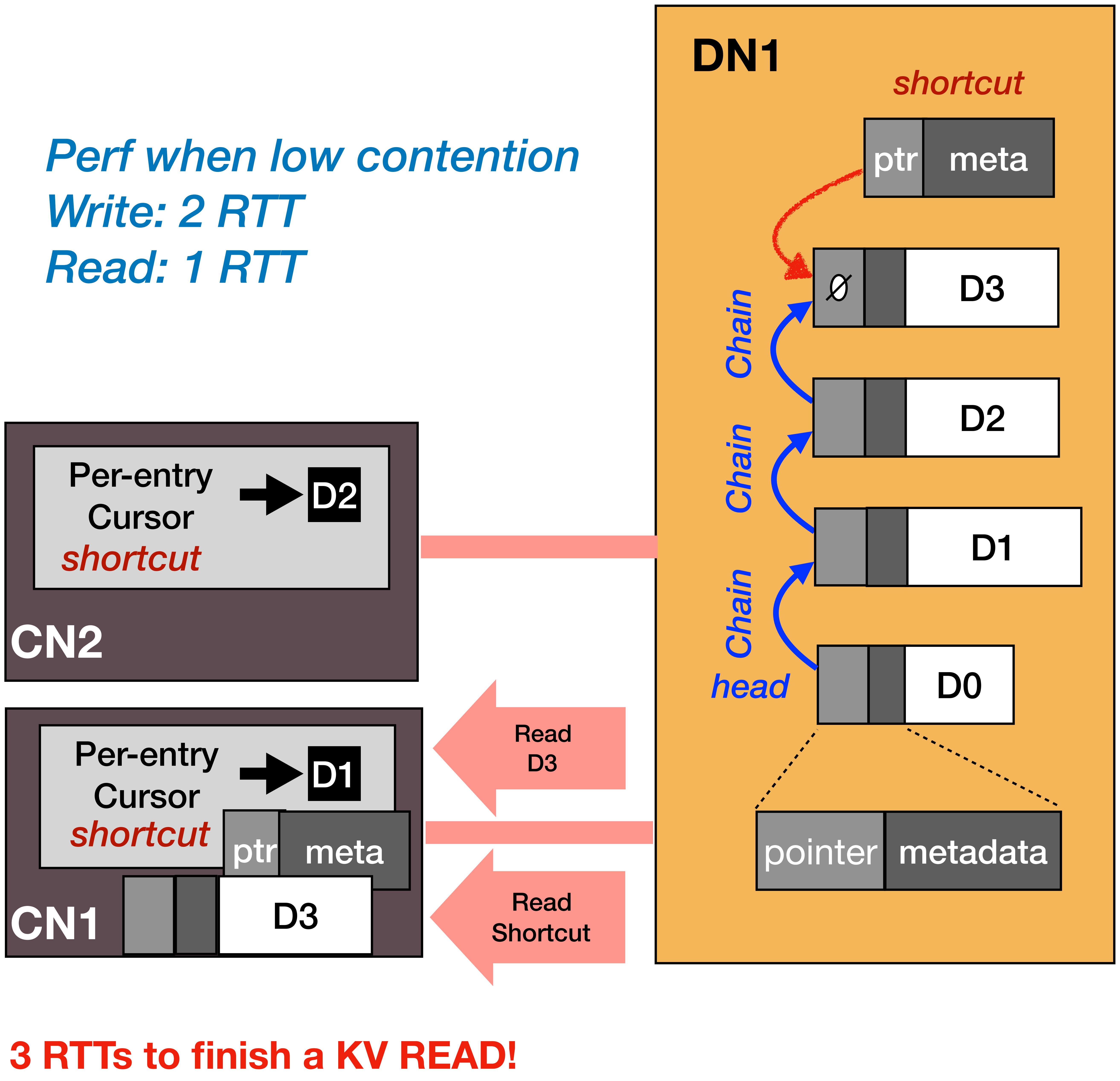

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Main Challenges in Metadata Plane:

How to provide low-overhead, scalable metadata service?

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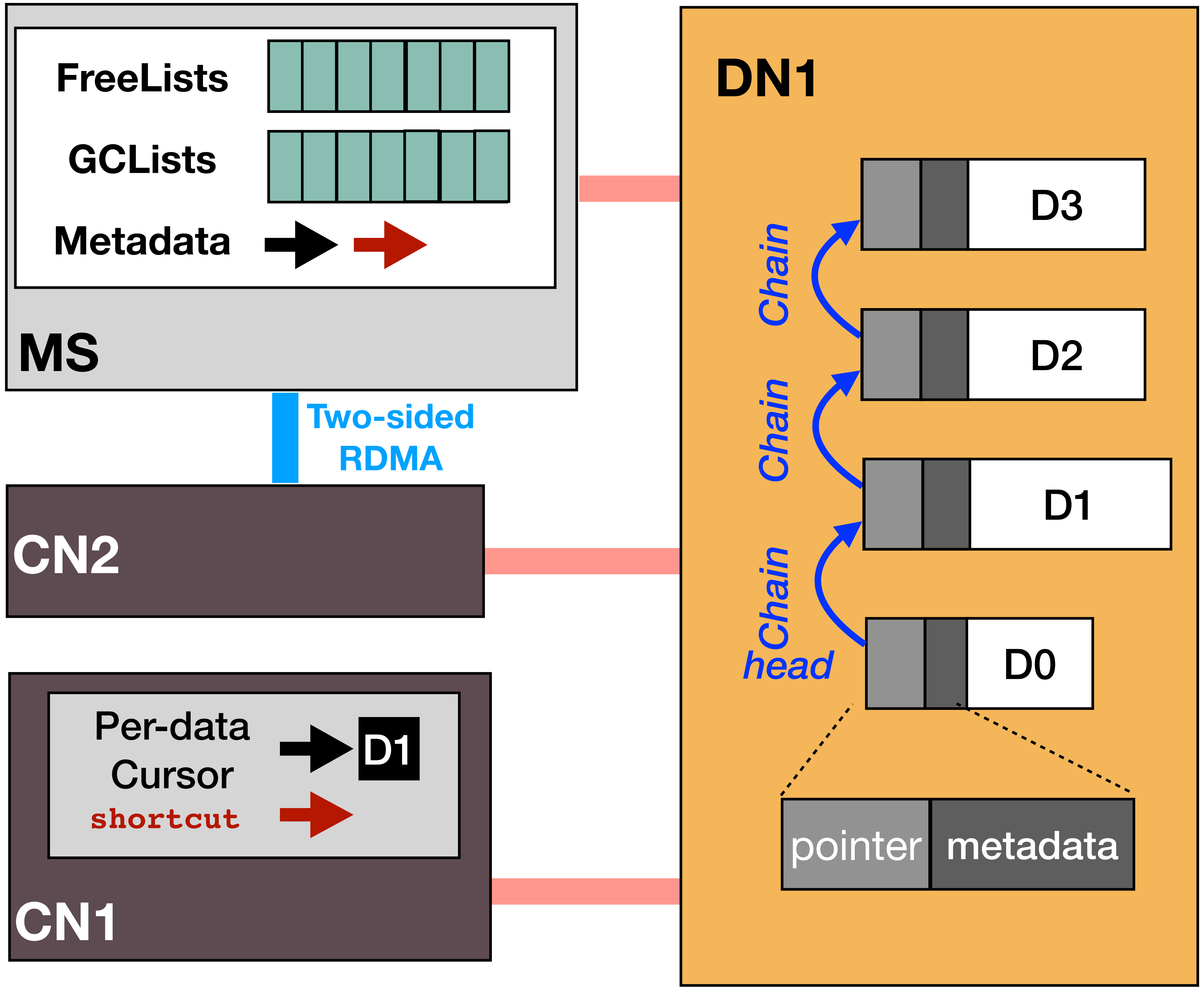
How to provide low-overhead, scalable metadata service?

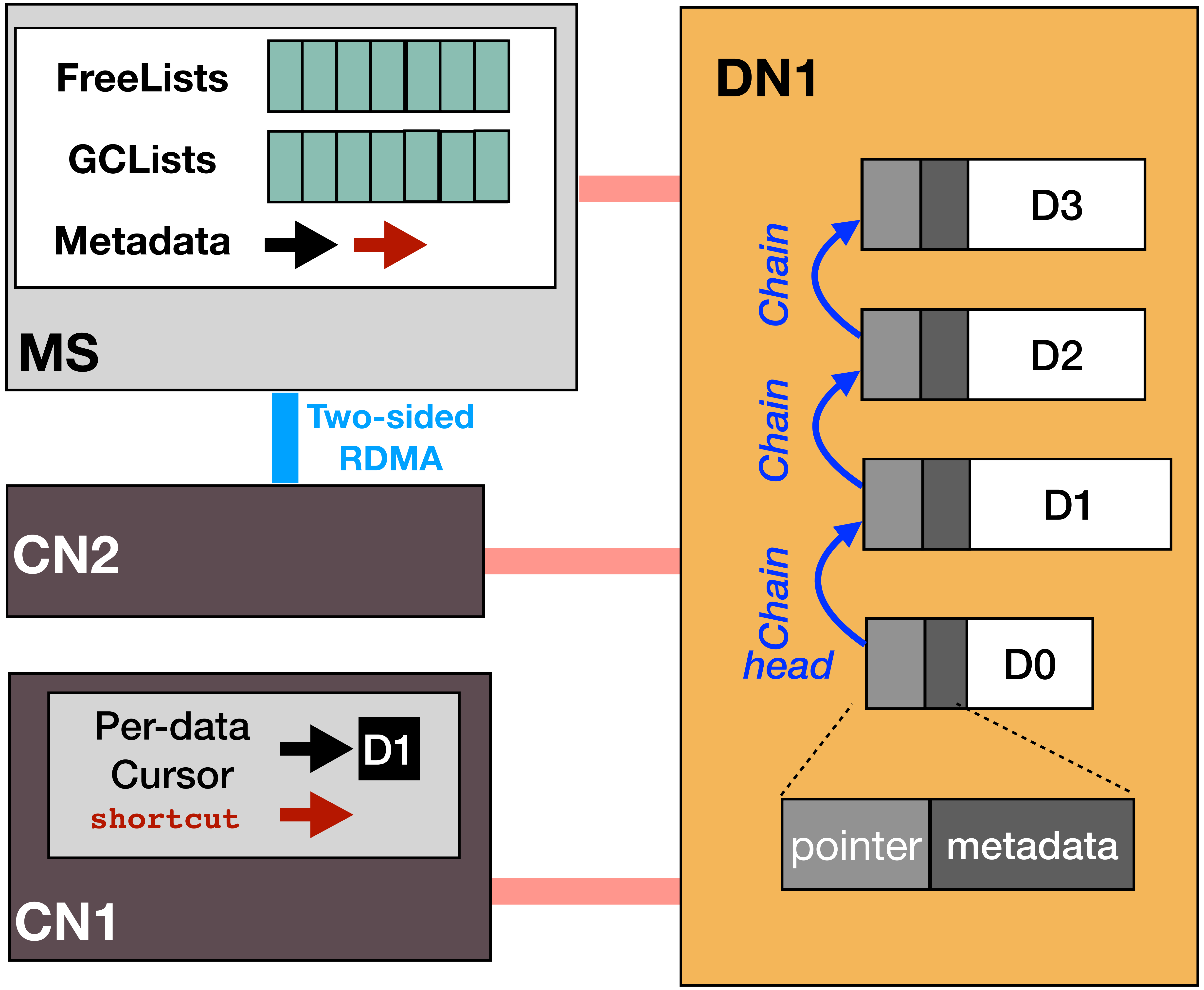
Our Approaches

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

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

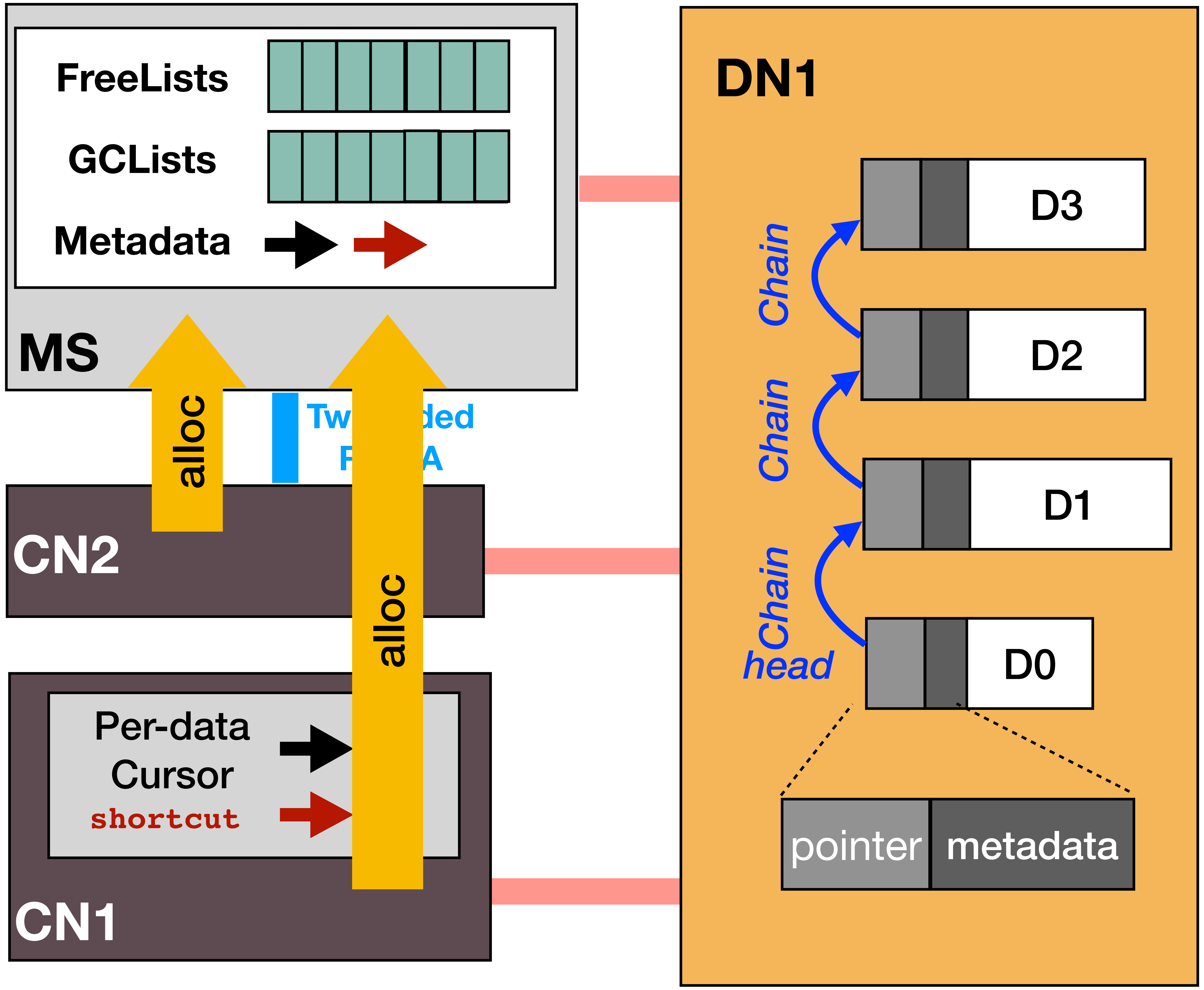
Metadata Server (MS)





Metadata Server (MS)

- Space management
- Garbage collection
- Global load balancing



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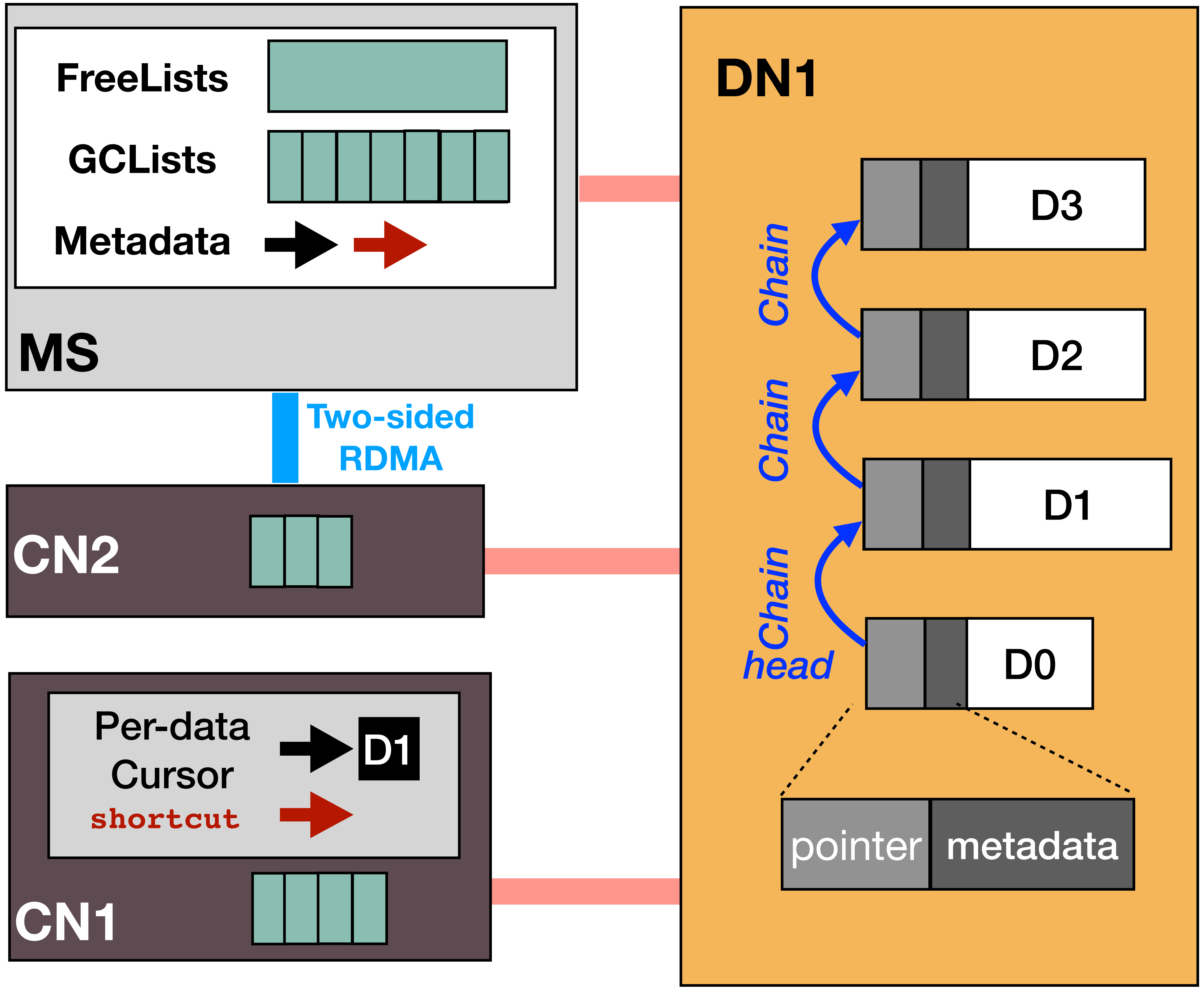

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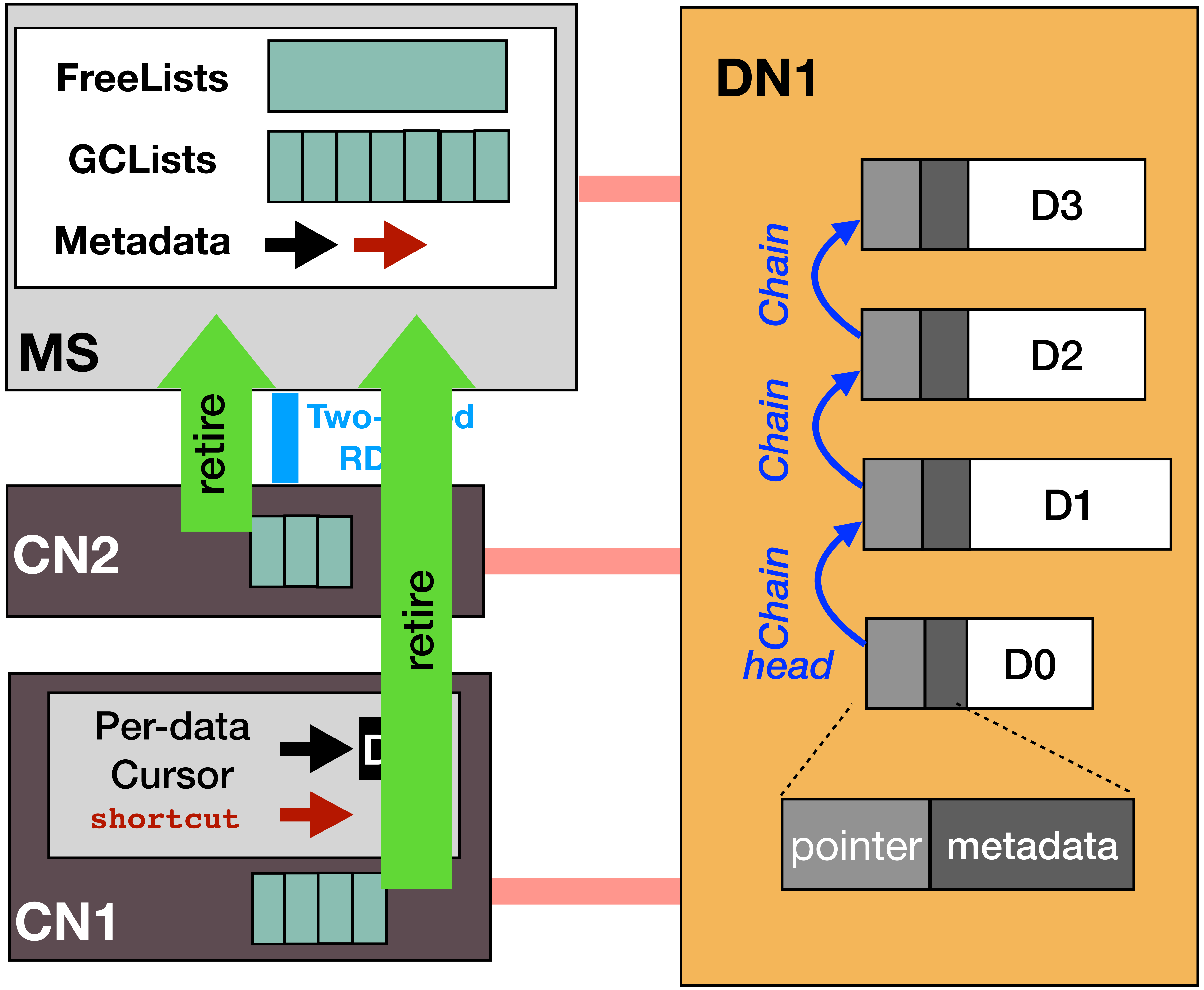

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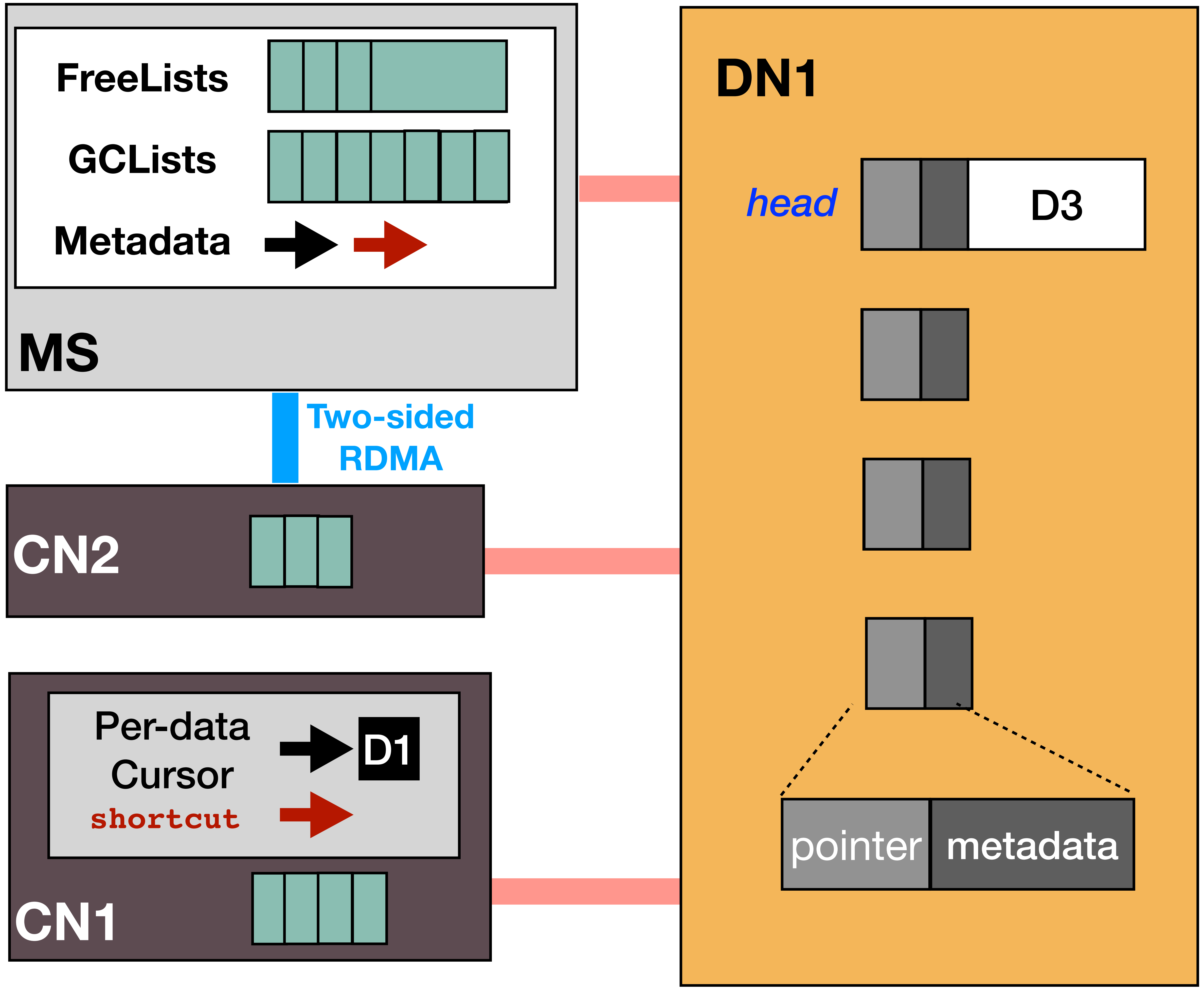

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Reliability and Load Balancing

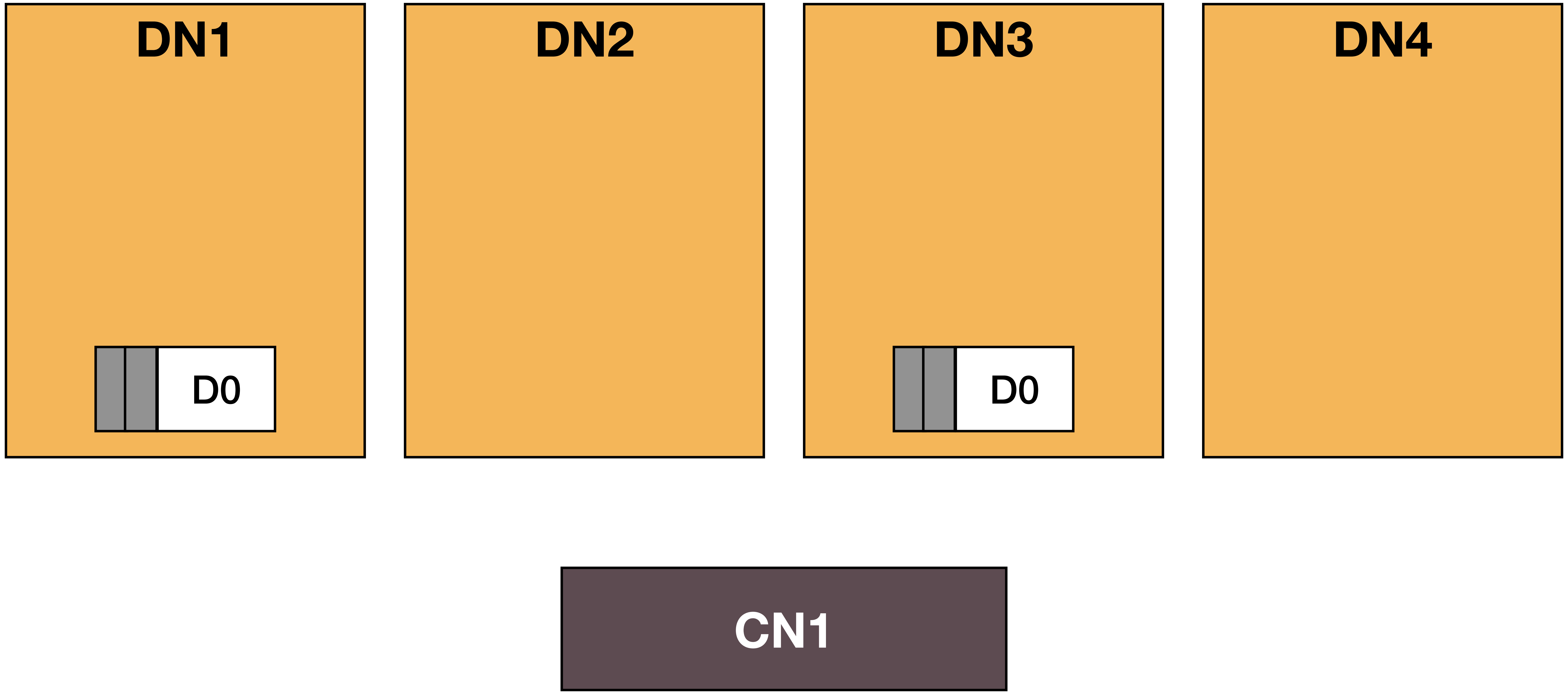
Data reliability through a novel chaining replication

- 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



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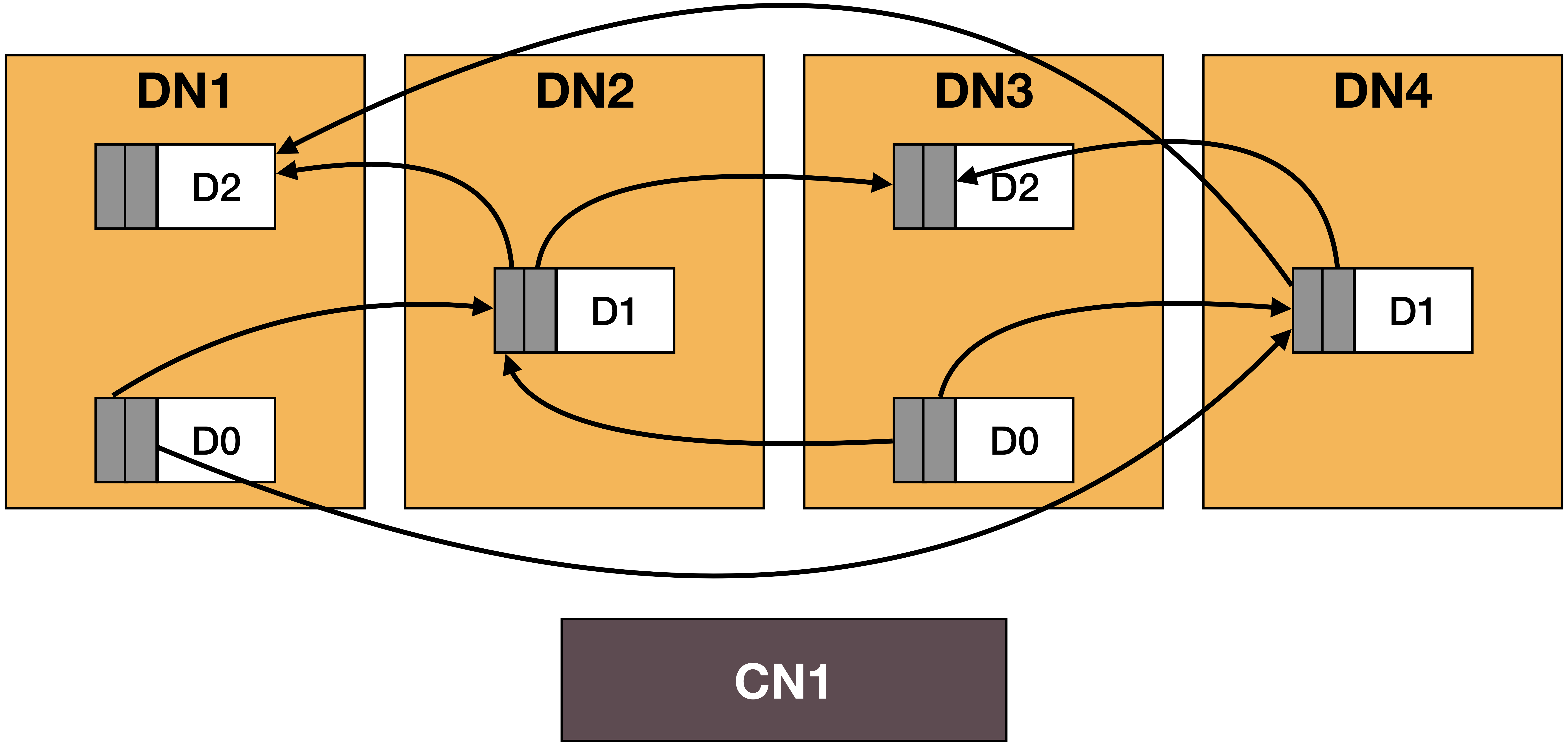
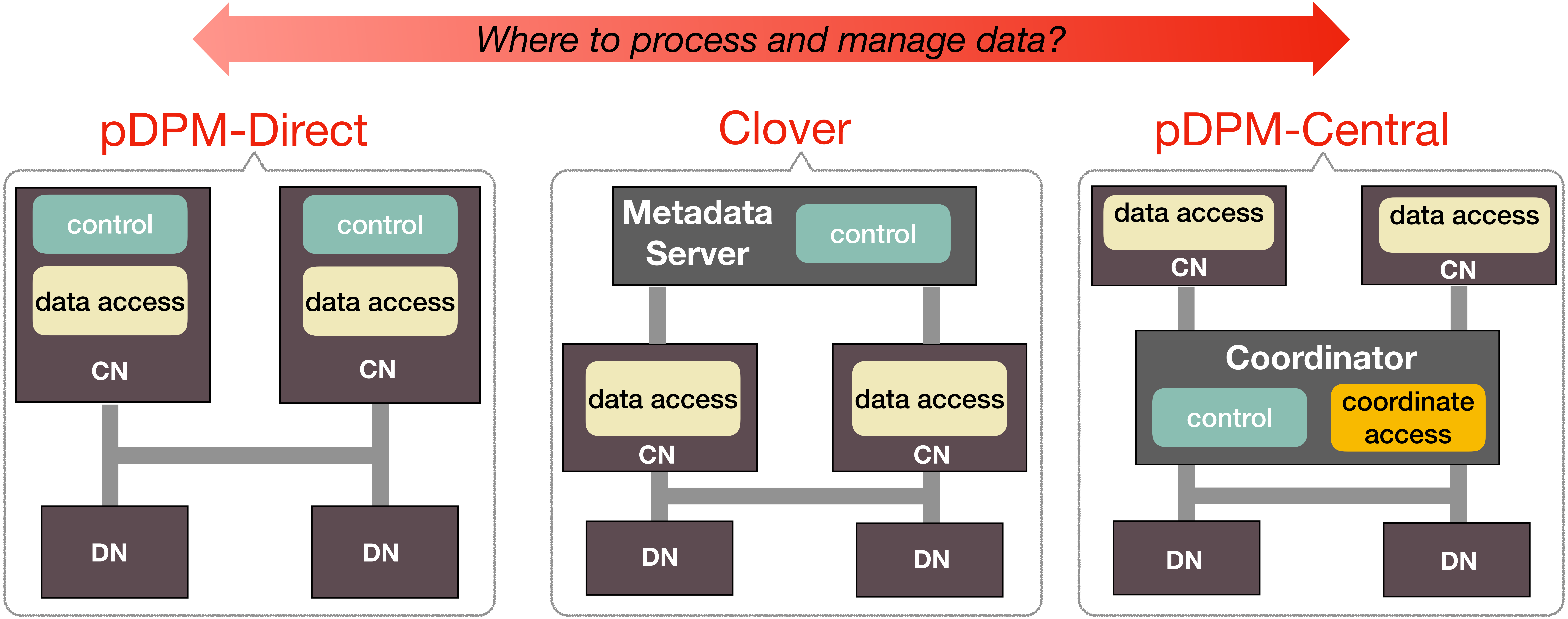




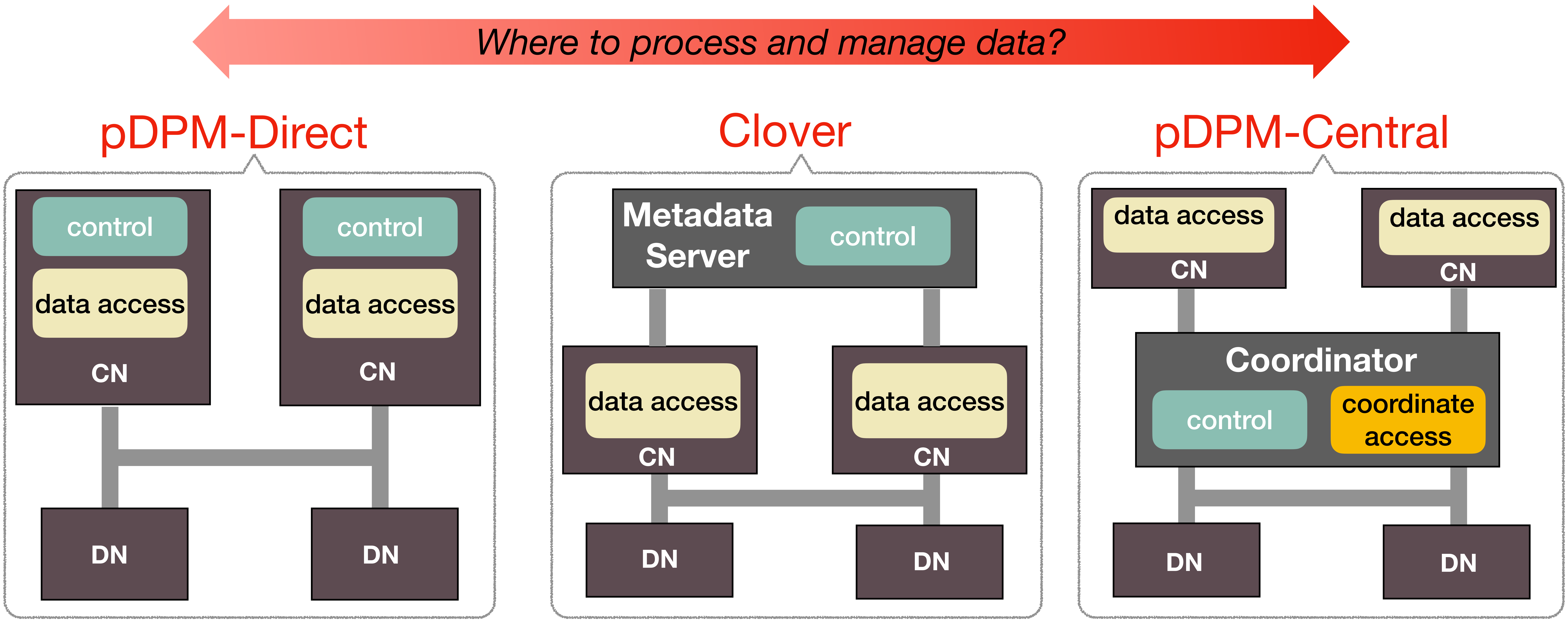
- Write cannot scale
- Large metadata consumption

- Extra read RTTs
- Coordinator cannot scale

Distributed data & metadata

Separate data & metadata

Centralized data & metadata



- Write cannot scale
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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

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

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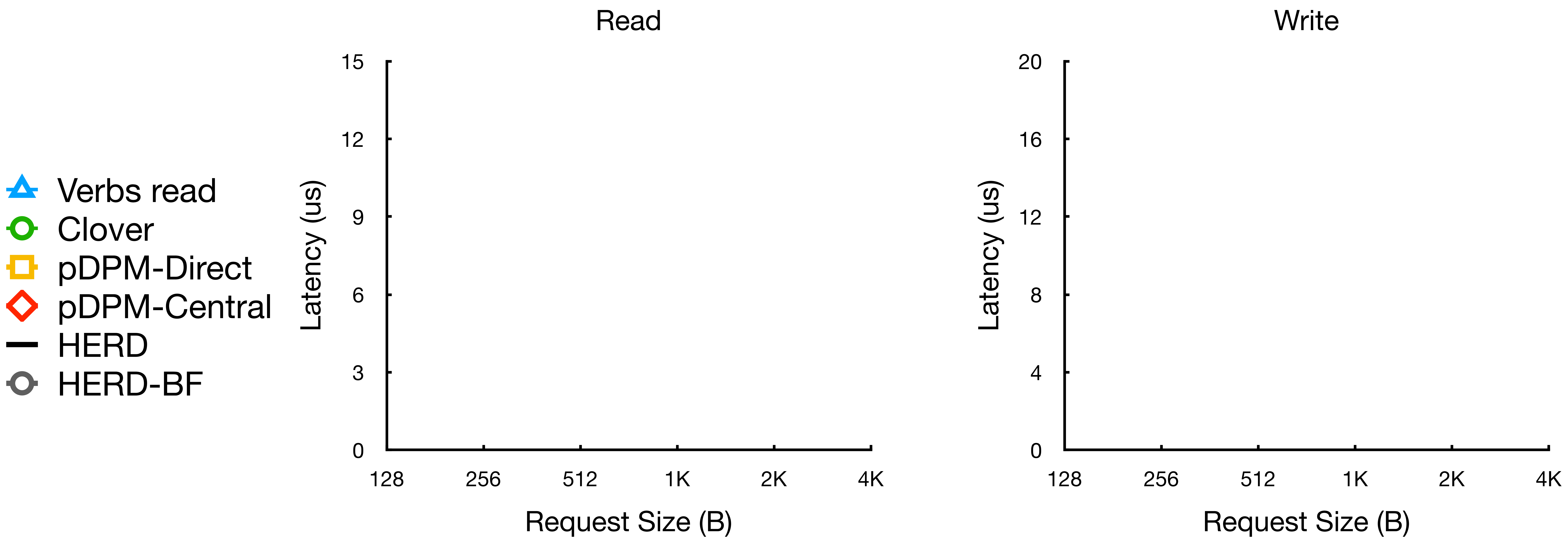

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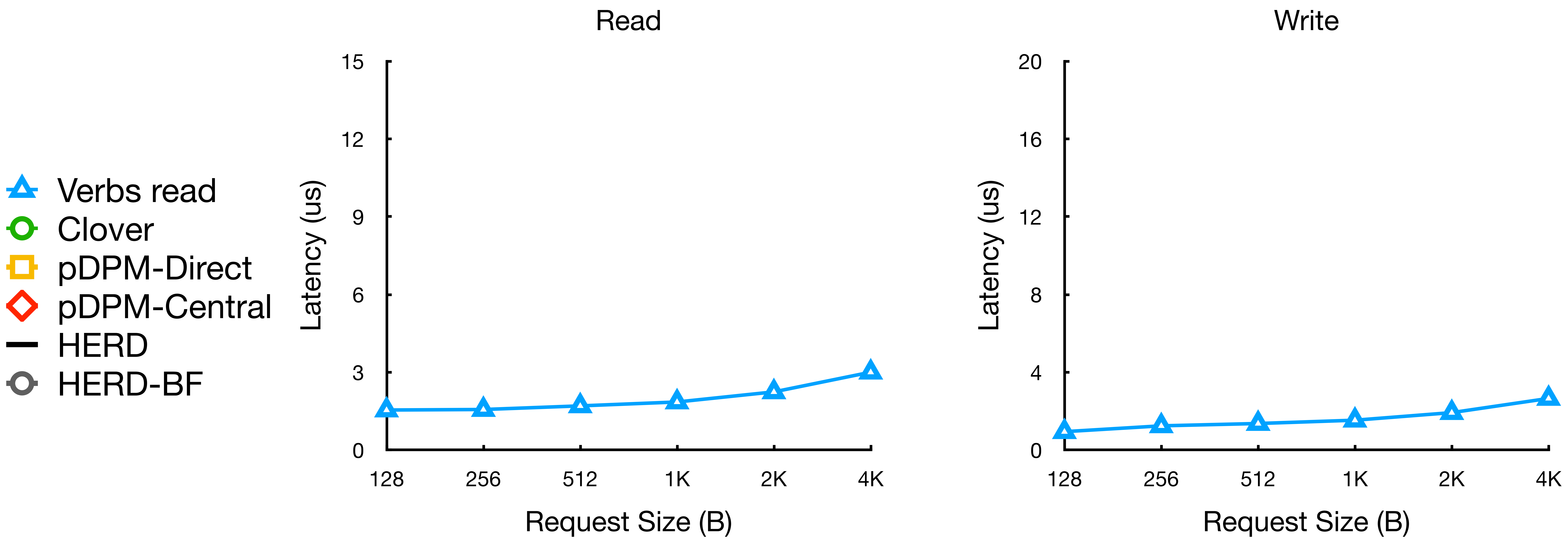

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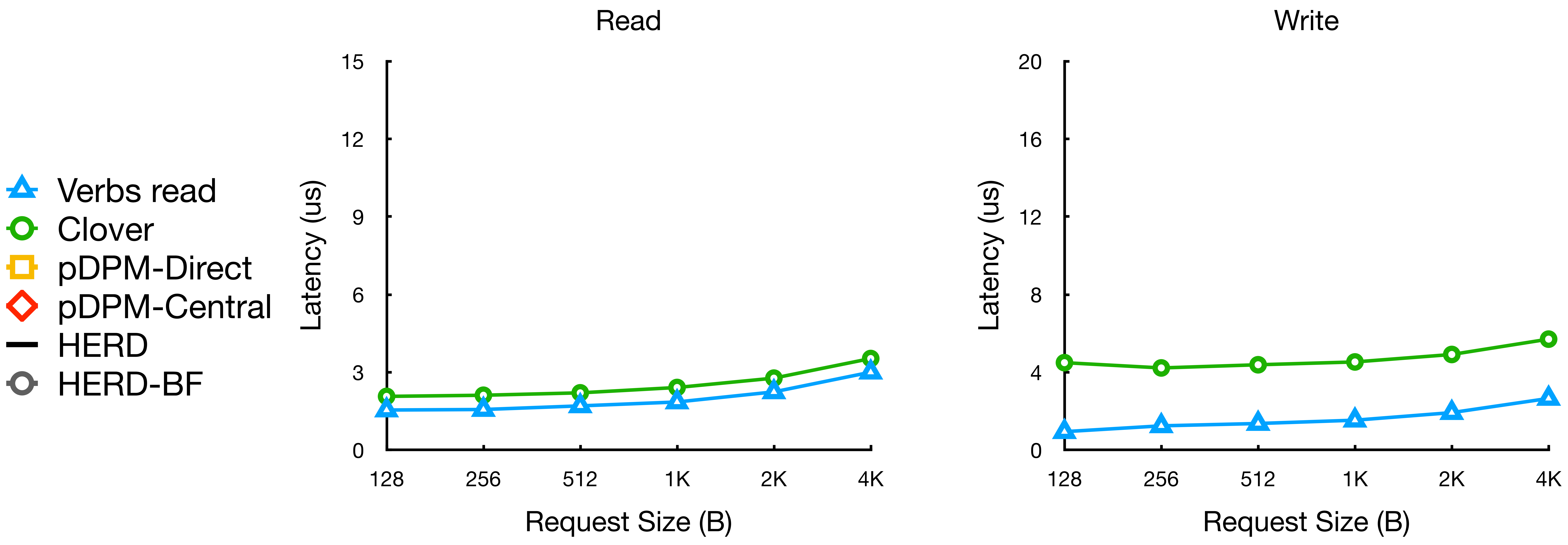

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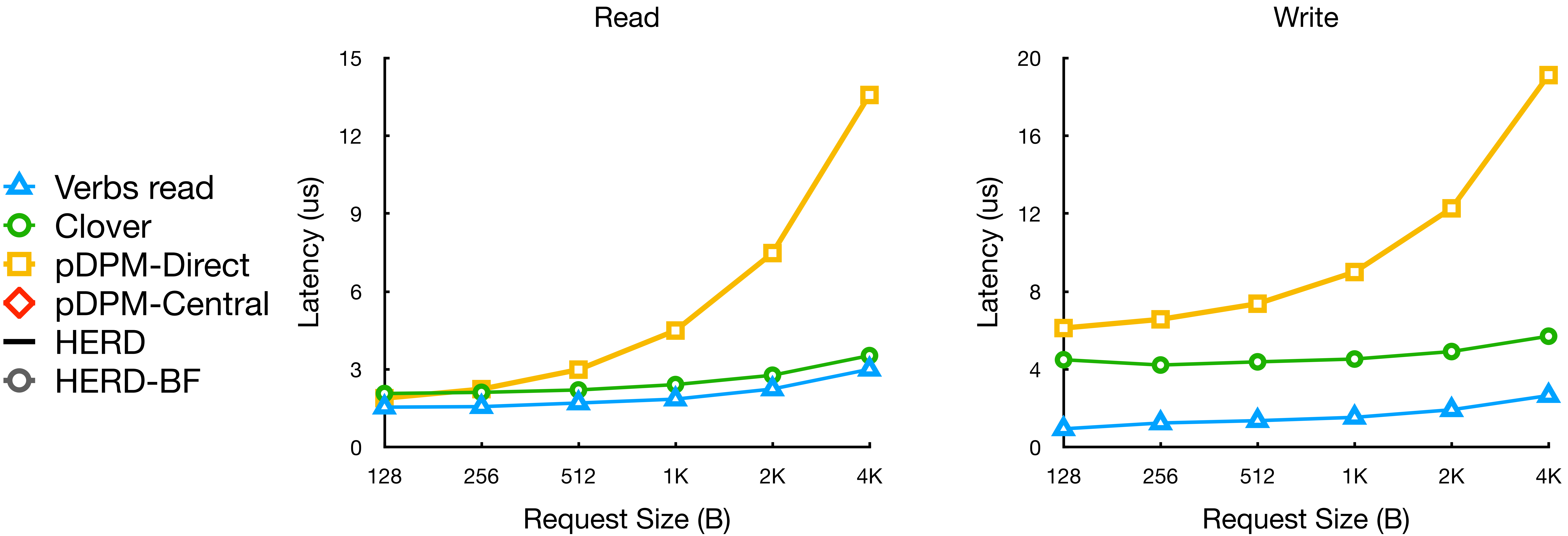

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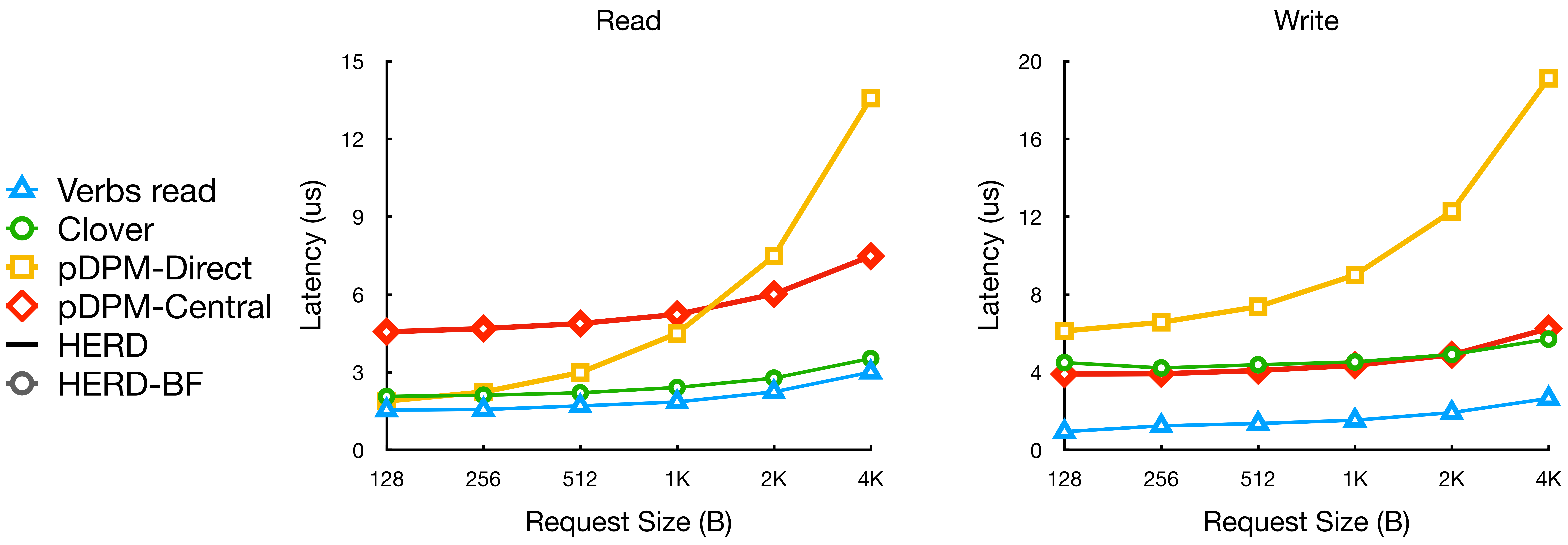

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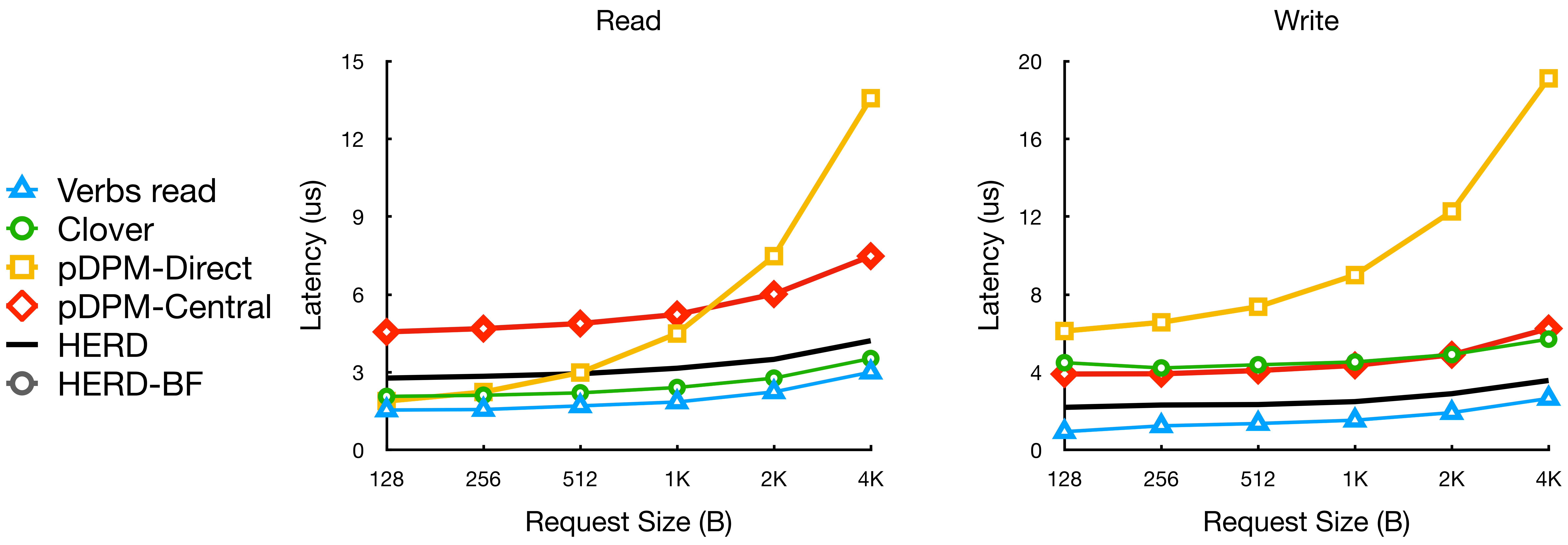

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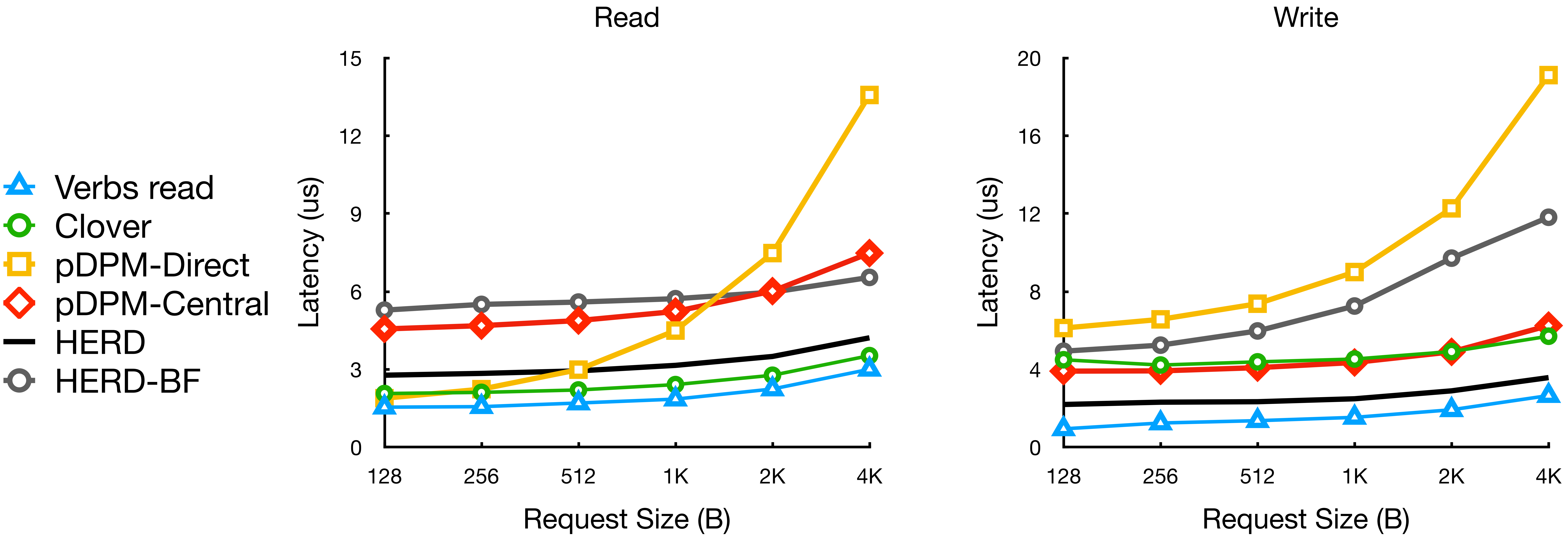

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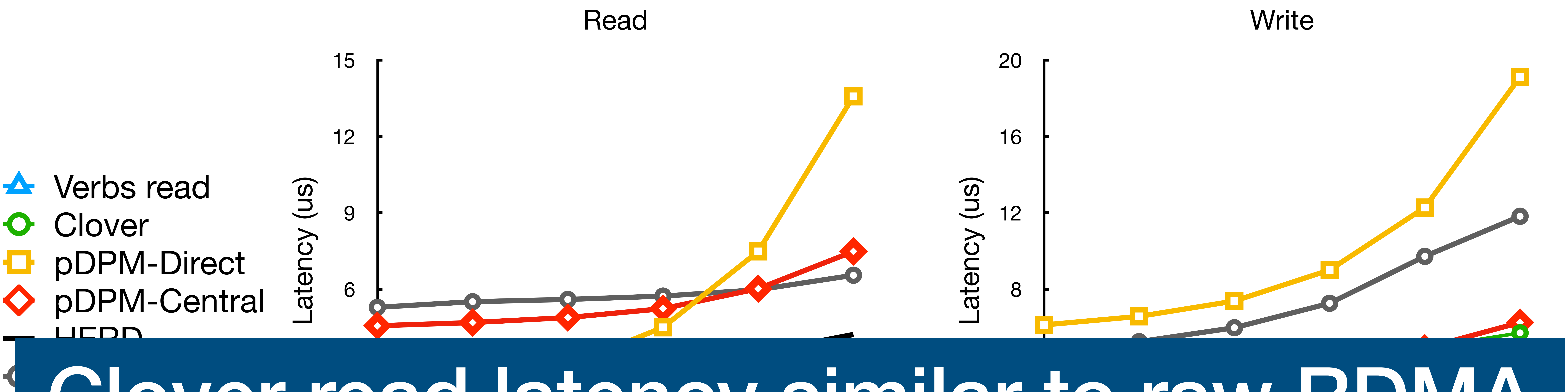

Clover read latency similar to raw RDMA
write latency around 2x of raw RDMA

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YCSB Results

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

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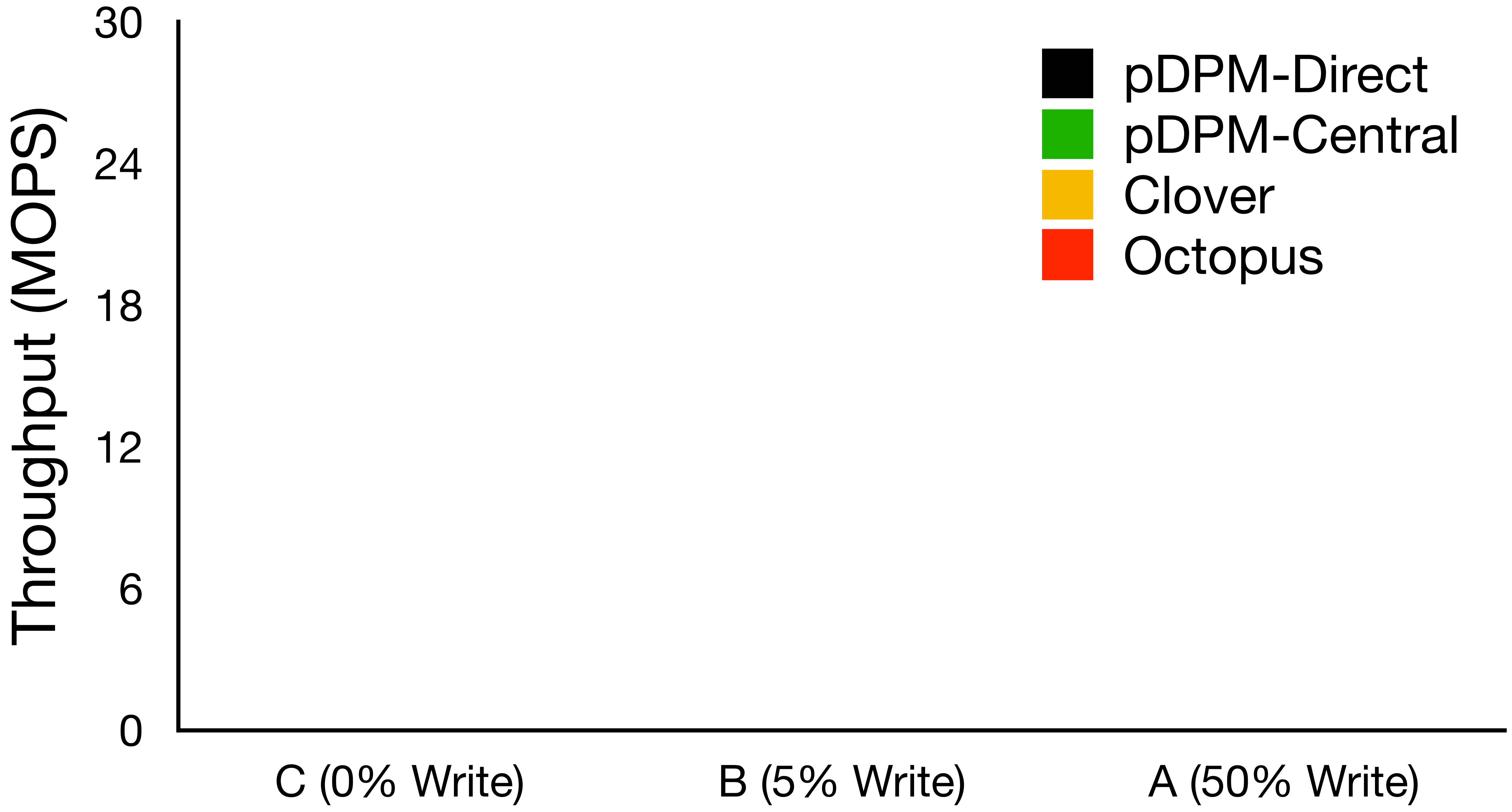

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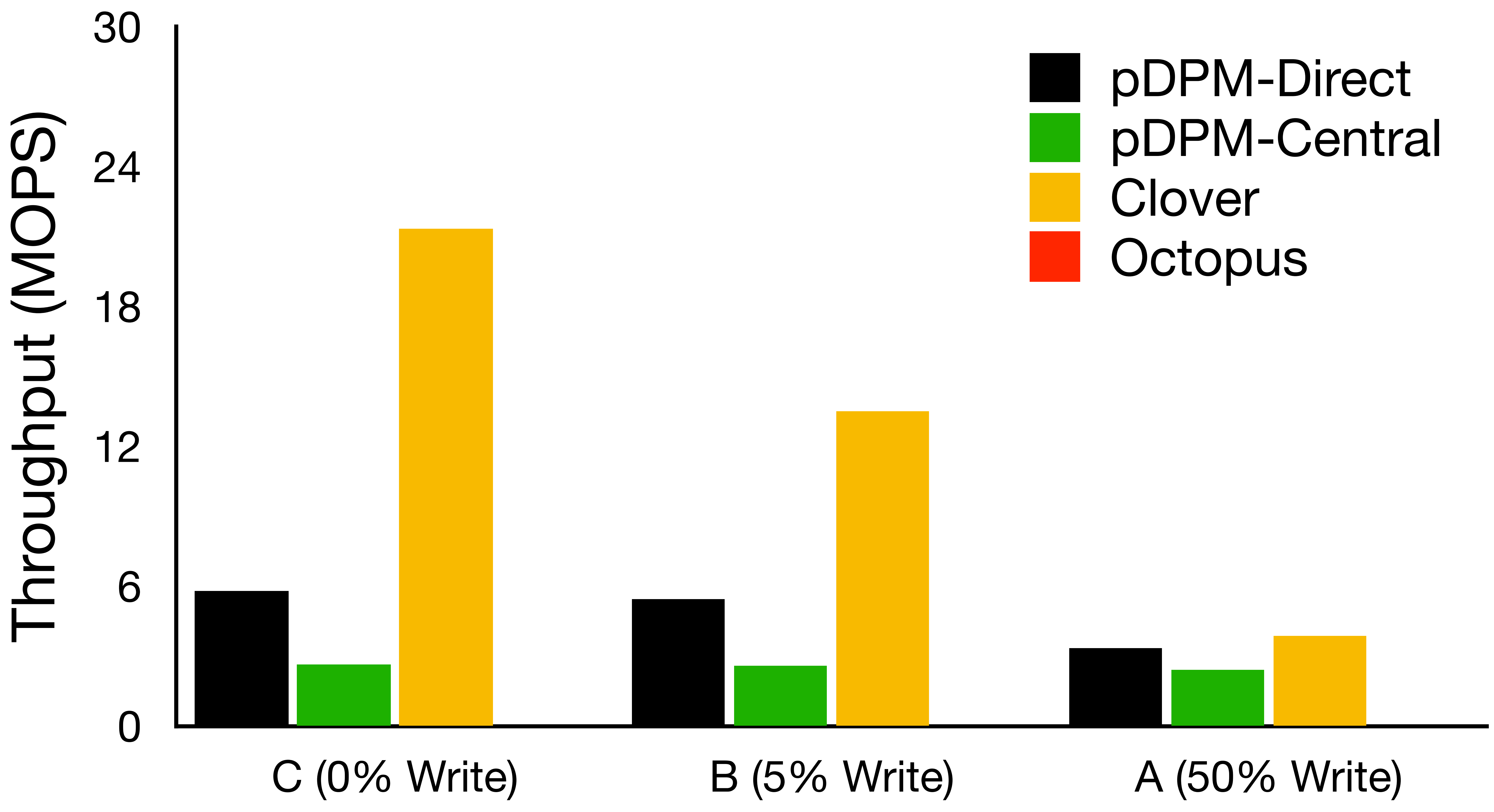

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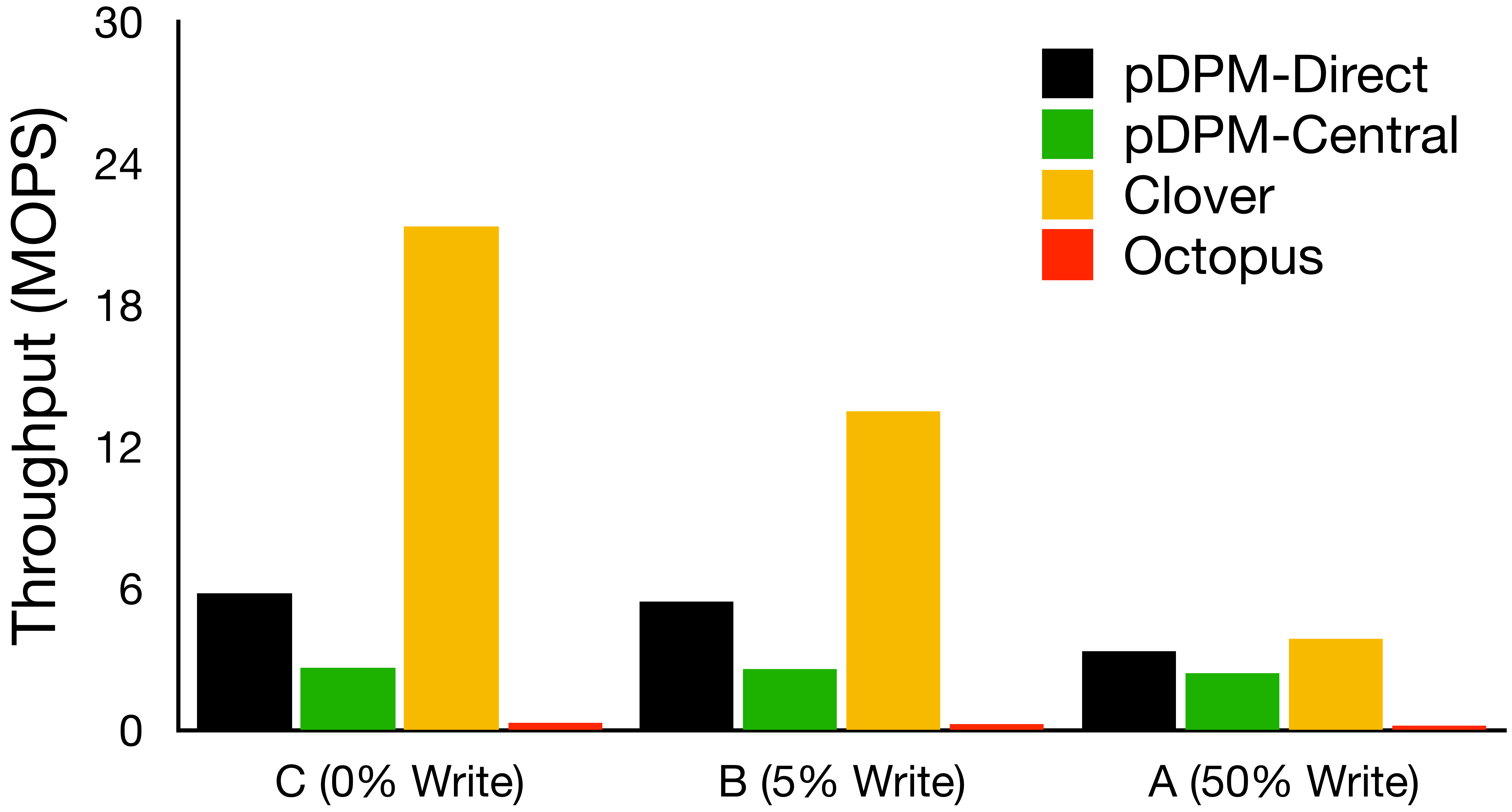

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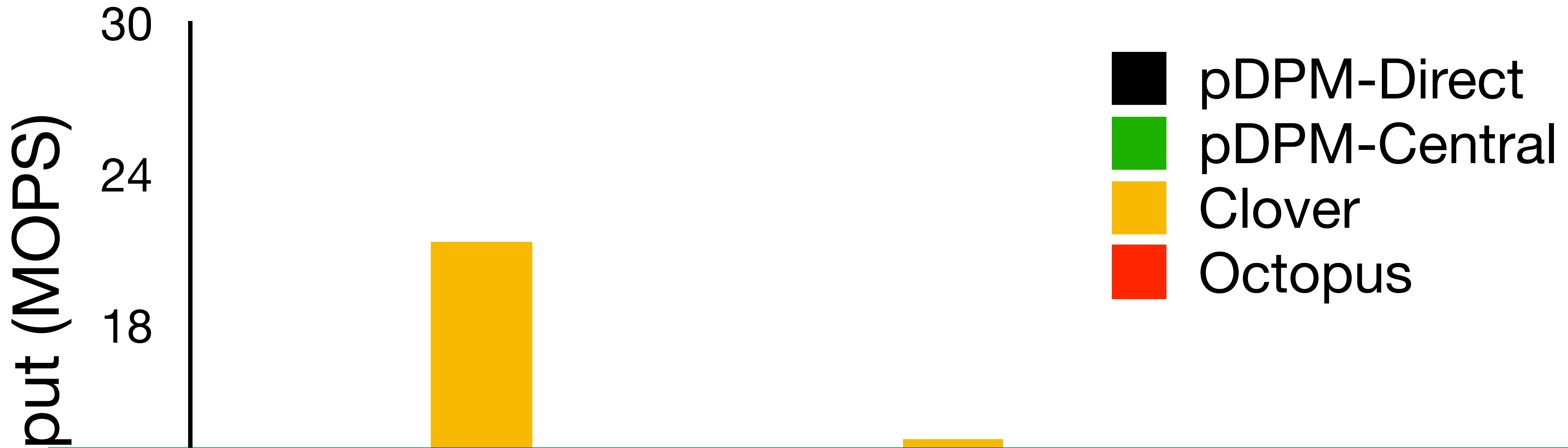

Clover outperforms non-disaggregated PM systems and is similar to aDPM under common cases (worse under heavy concurrent writes)

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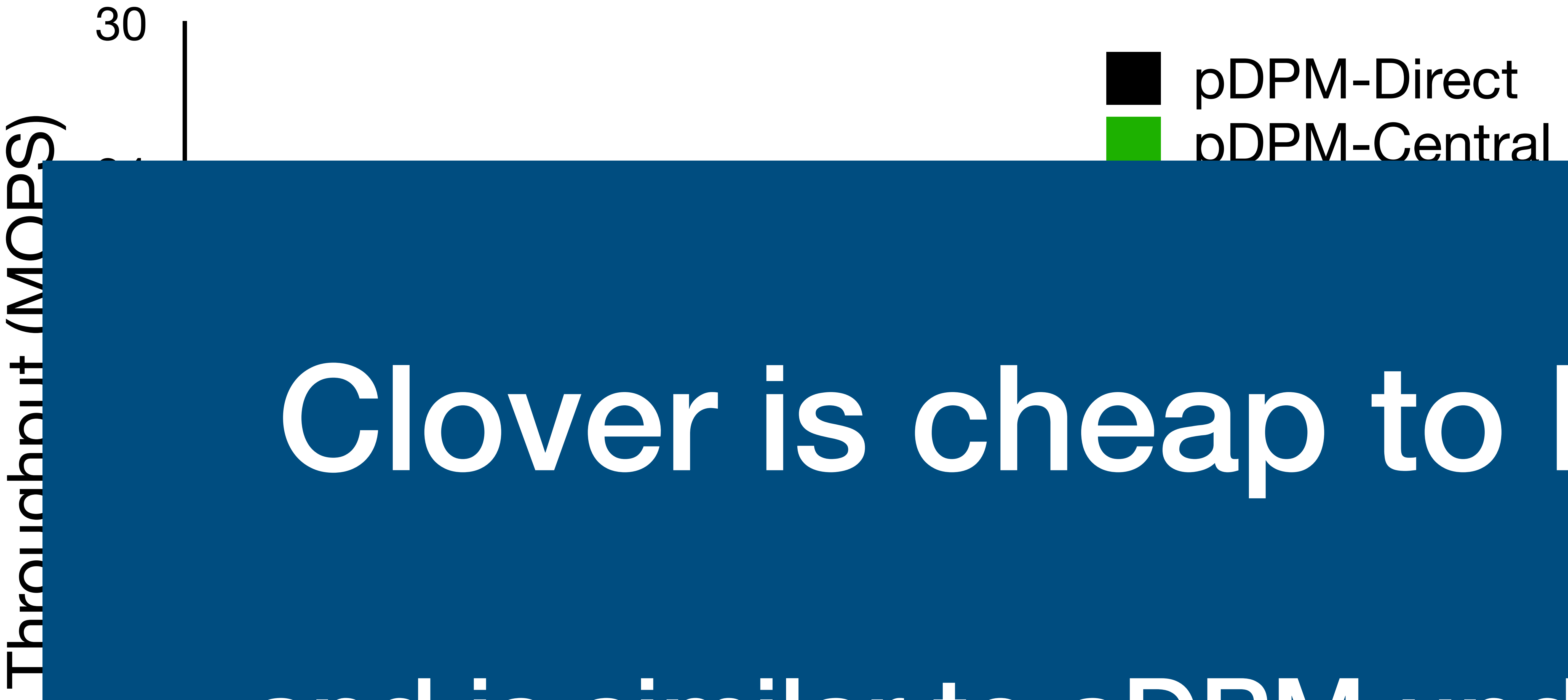

Clover is cheap to build and run

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

- 100K KV entries, 1 million operations, Zipf access distribution
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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

Thank you!

open source @ github.com/WukLab/pDPM

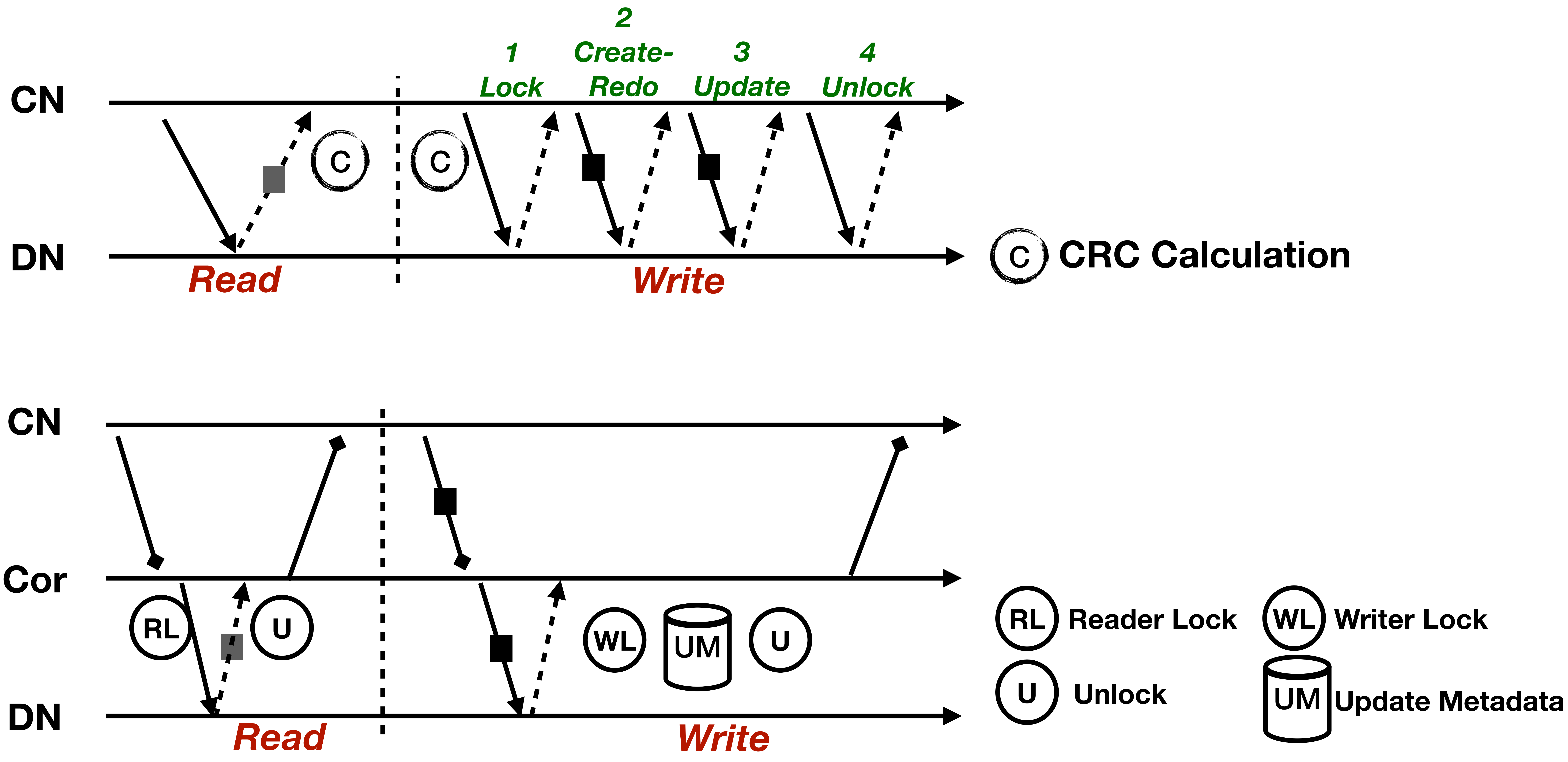
WukLab.io

PURDUE UNIVERSITY

UC San Diego

Backup Slides

pDPM-Direct/Central RW Protocols



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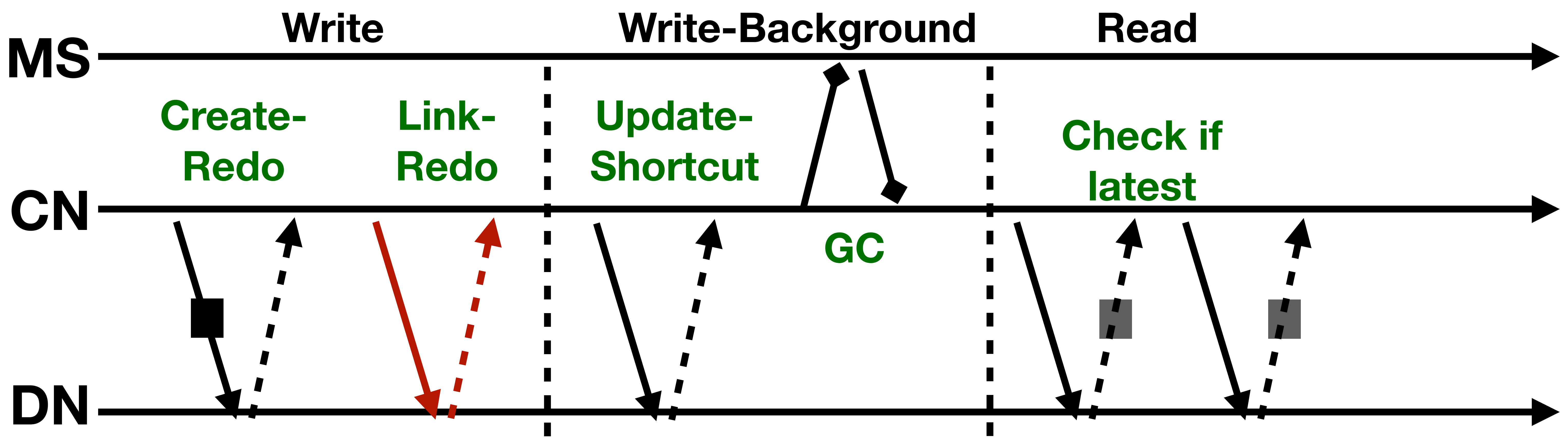

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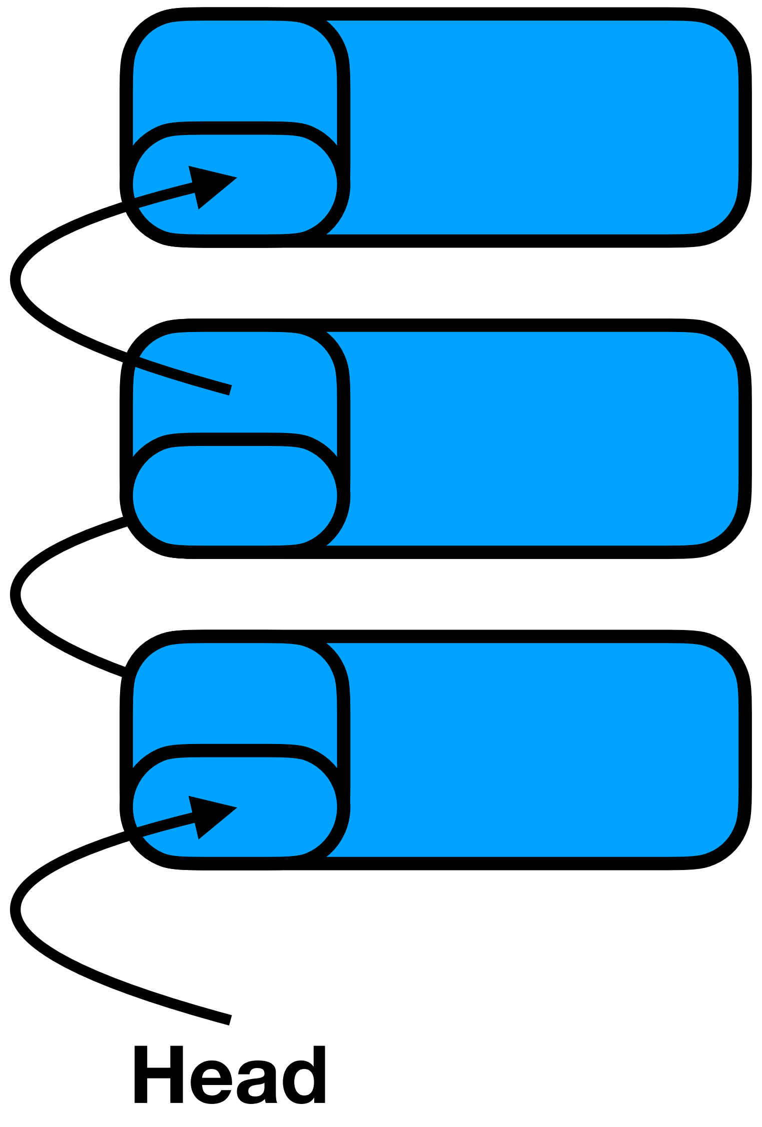

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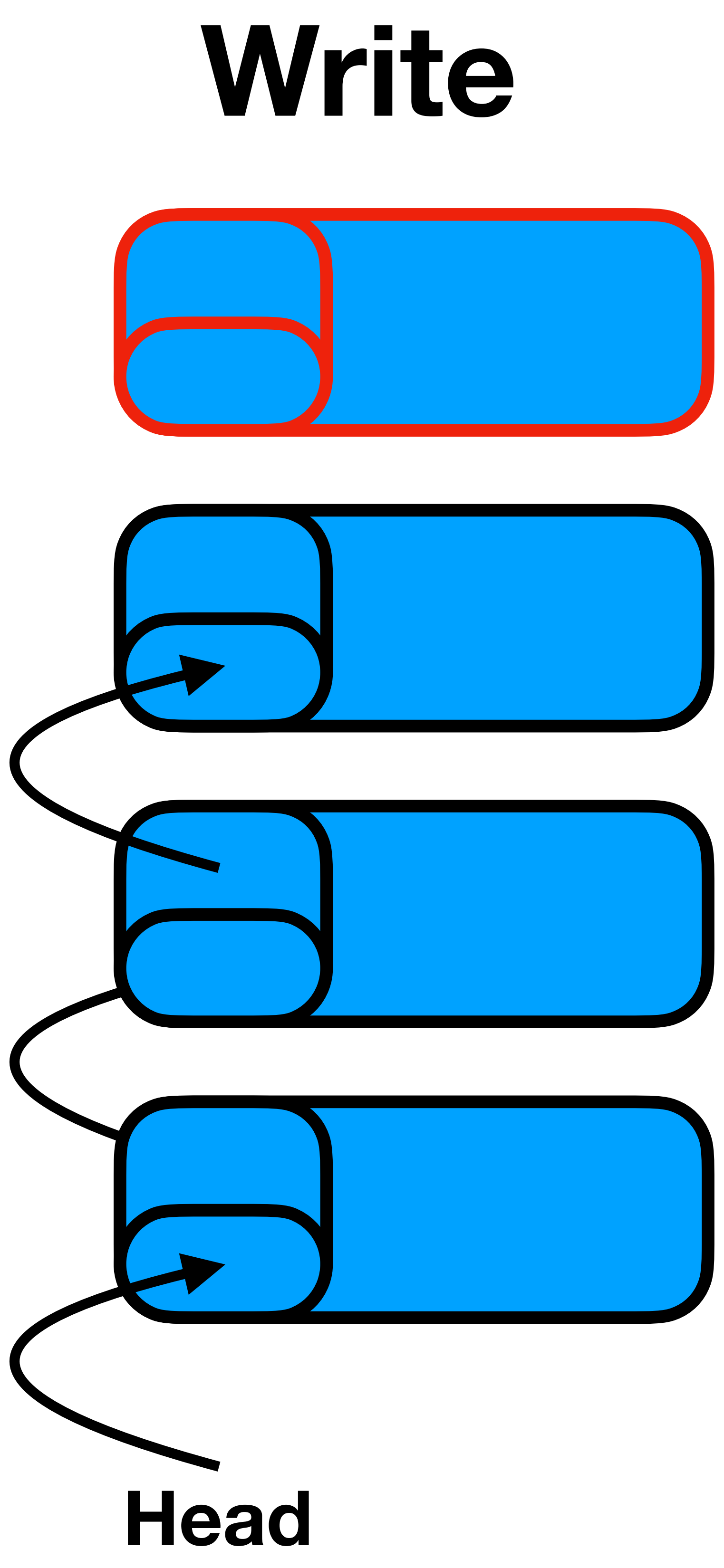

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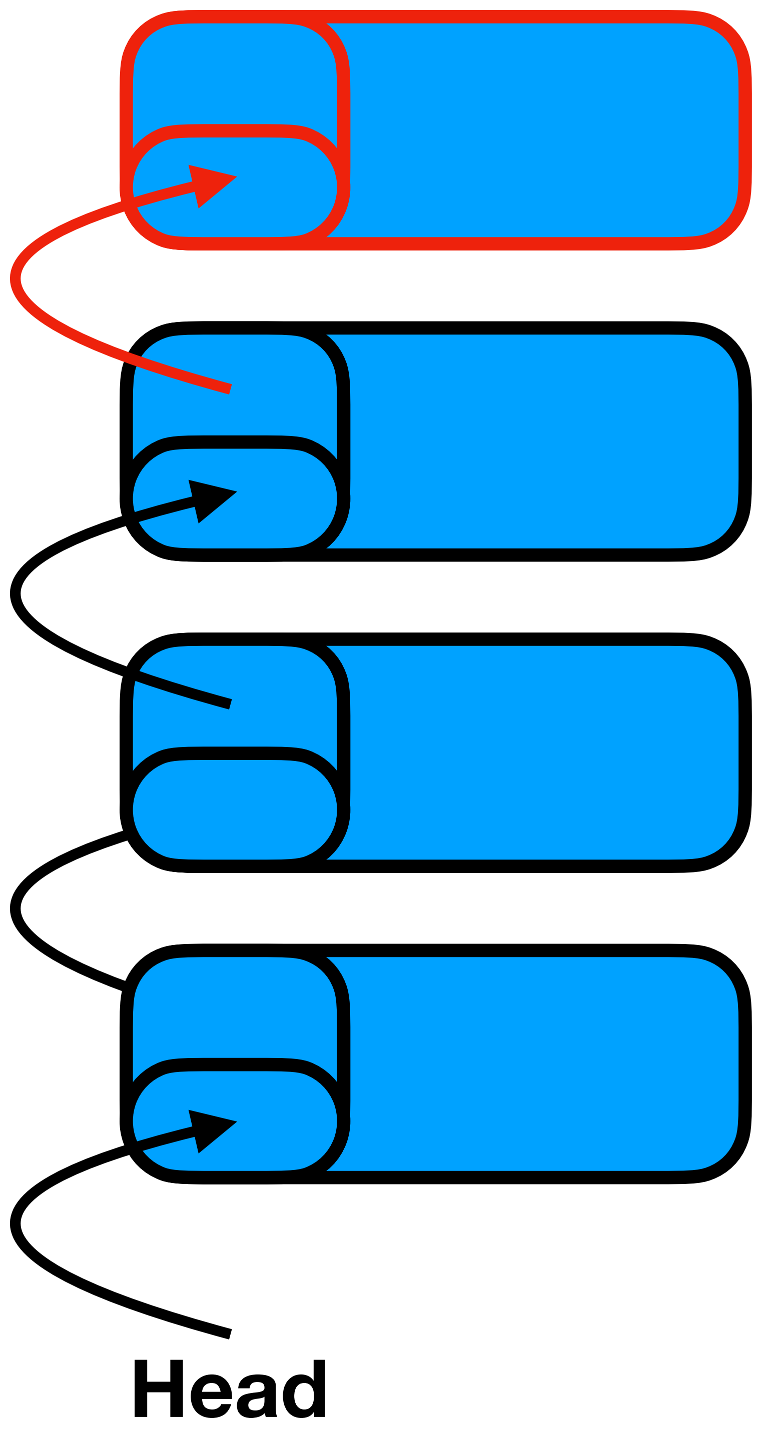

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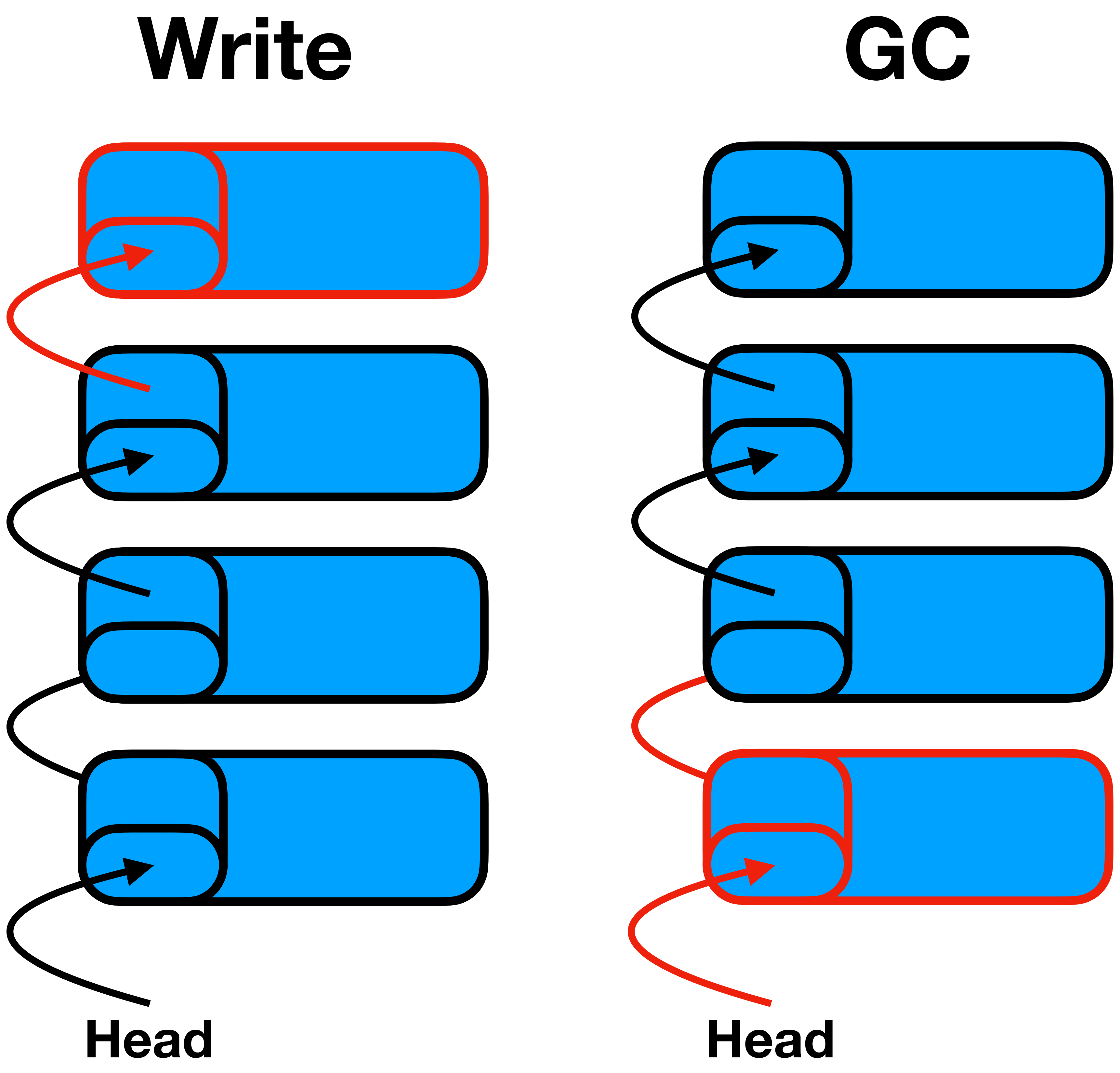

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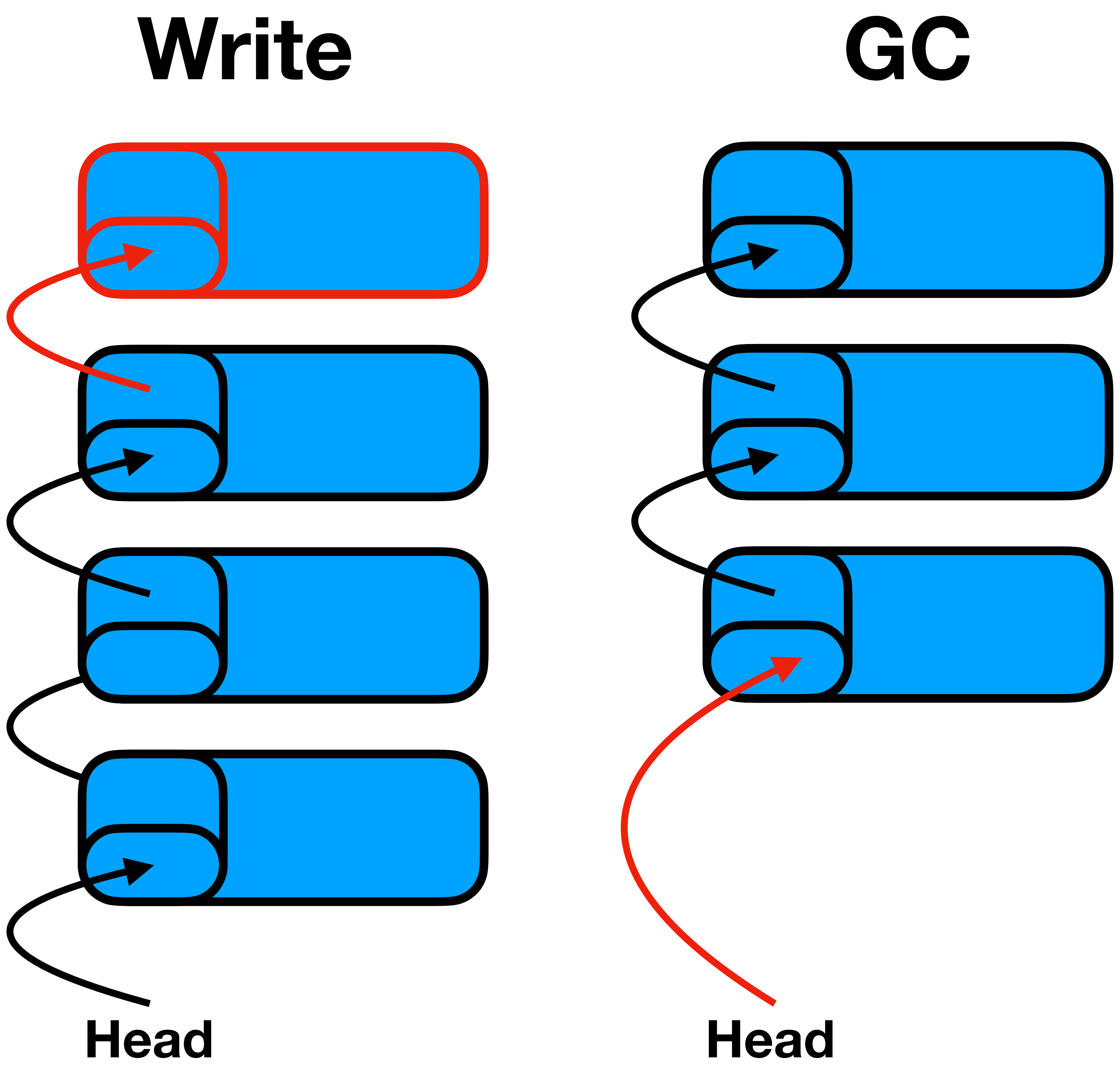

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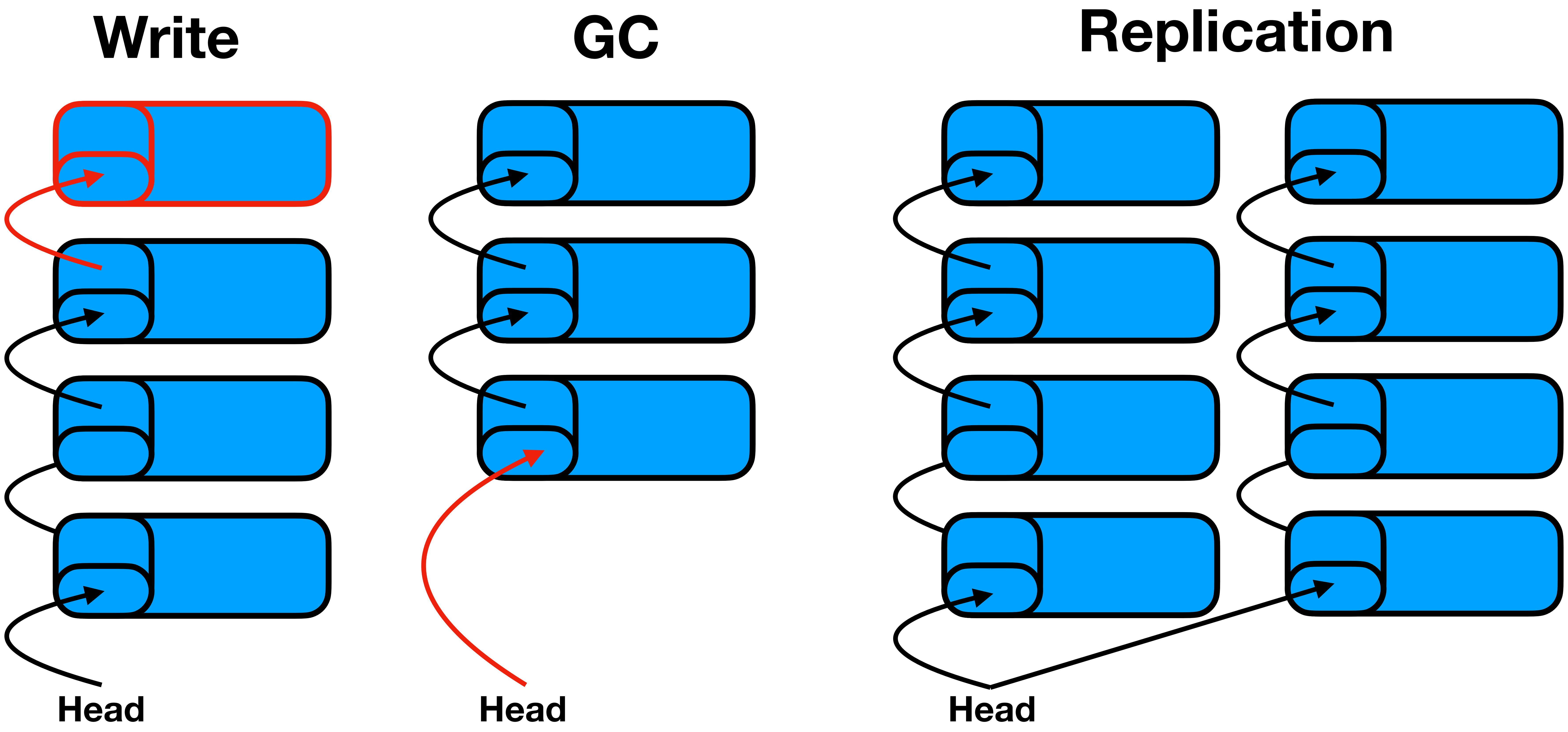

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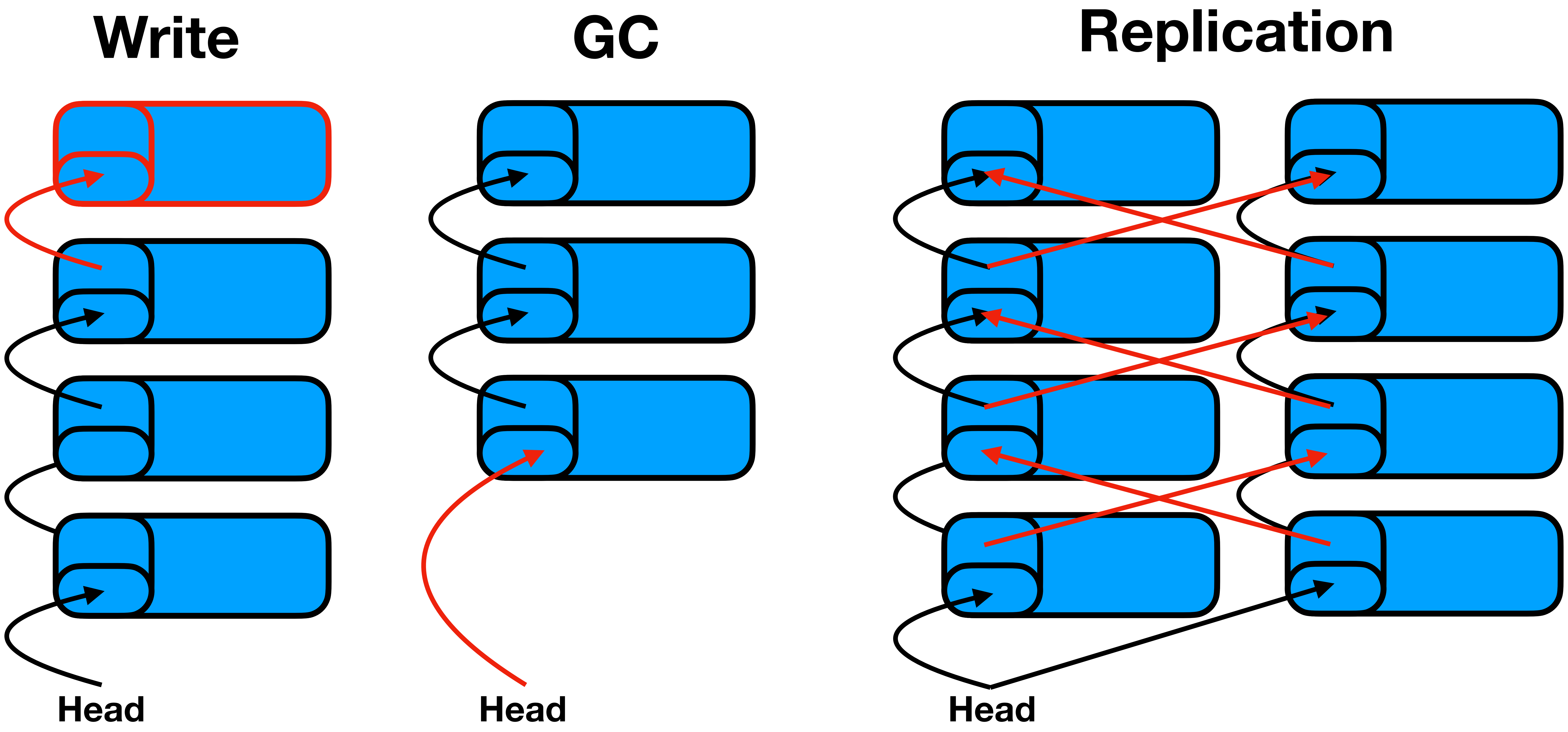

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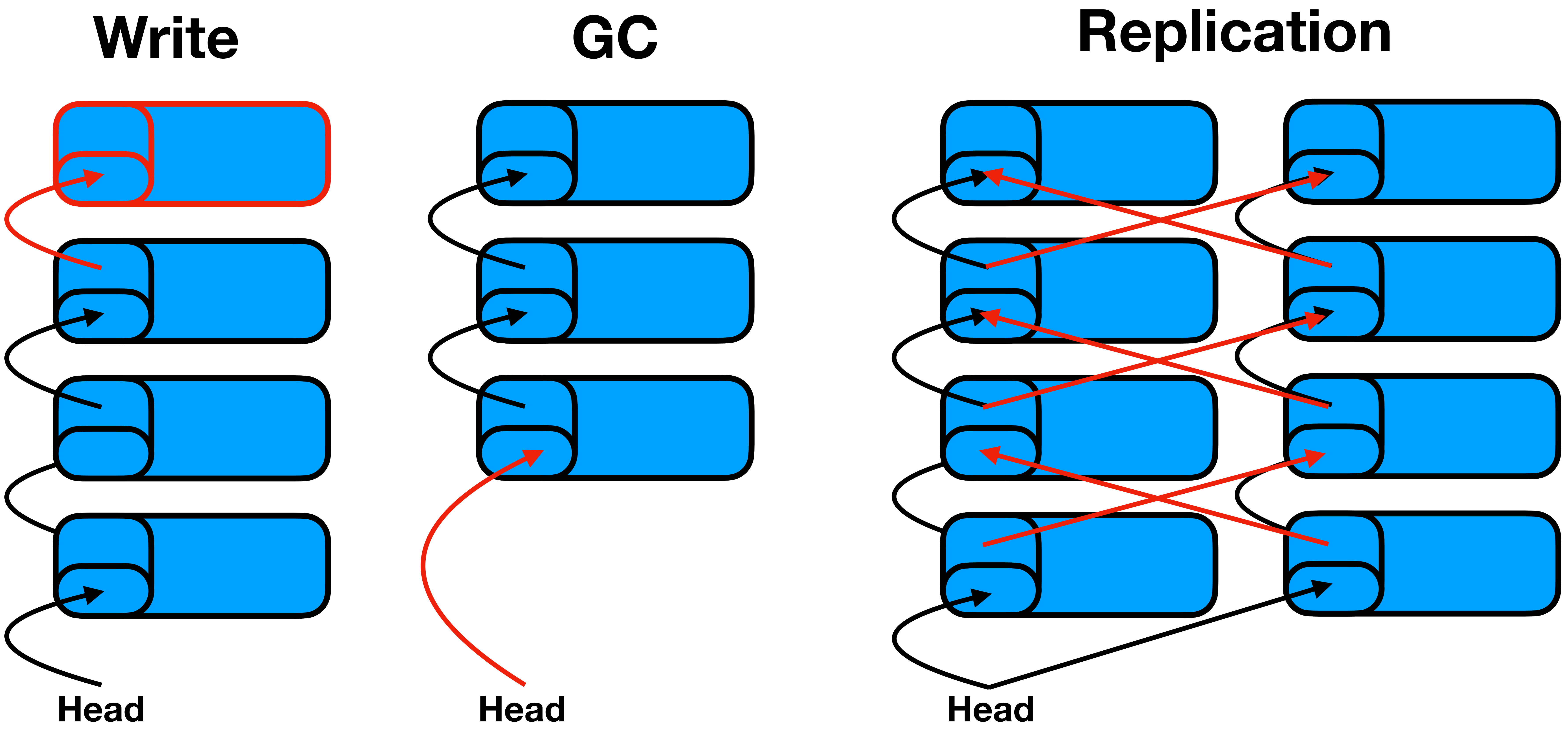

Load Balancing

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

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?