ODRP: On-Demand Remote Paging with Programmable RDMA

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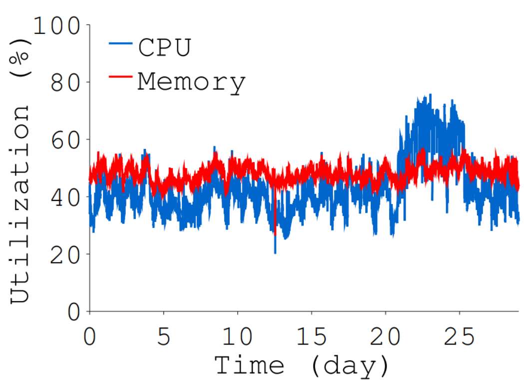
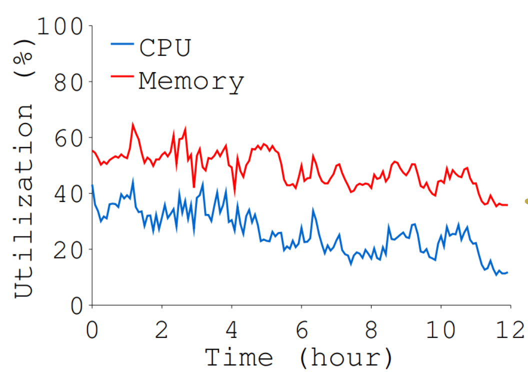
Low Memory Utilization in Datacenters

- **Over-provisioning Memory**
  - The memory demand of memory-intensive applications ***varies*** over time.
  - Datacenters allocate memory based on their ***peak usage*** to meet their SLOs.



(a) Google Cluster

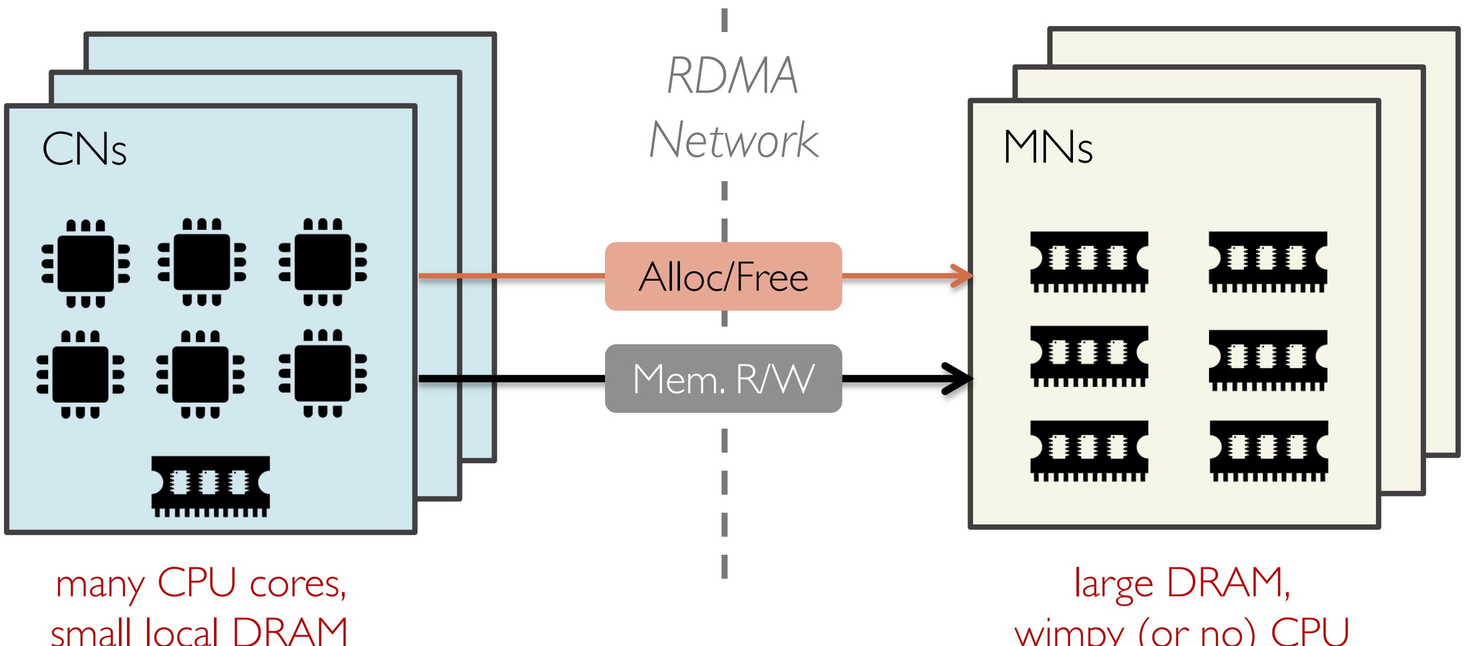


(b) Alibaba Cluster

Low average memory utilization!

Disaggregated Memory

- **Disaggregated Memory Architecture**
  - Physically separate CPU and memory resources into ***network-attached*** pools, namely compute nodes (CNs) and memory nodes (MNs).



Disaggregated Memory Management

- **Memory Management in DM relies on Memory Region (MR).**
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  - Requirement #2: Ensure ***Memory Isolation*** between CNs.

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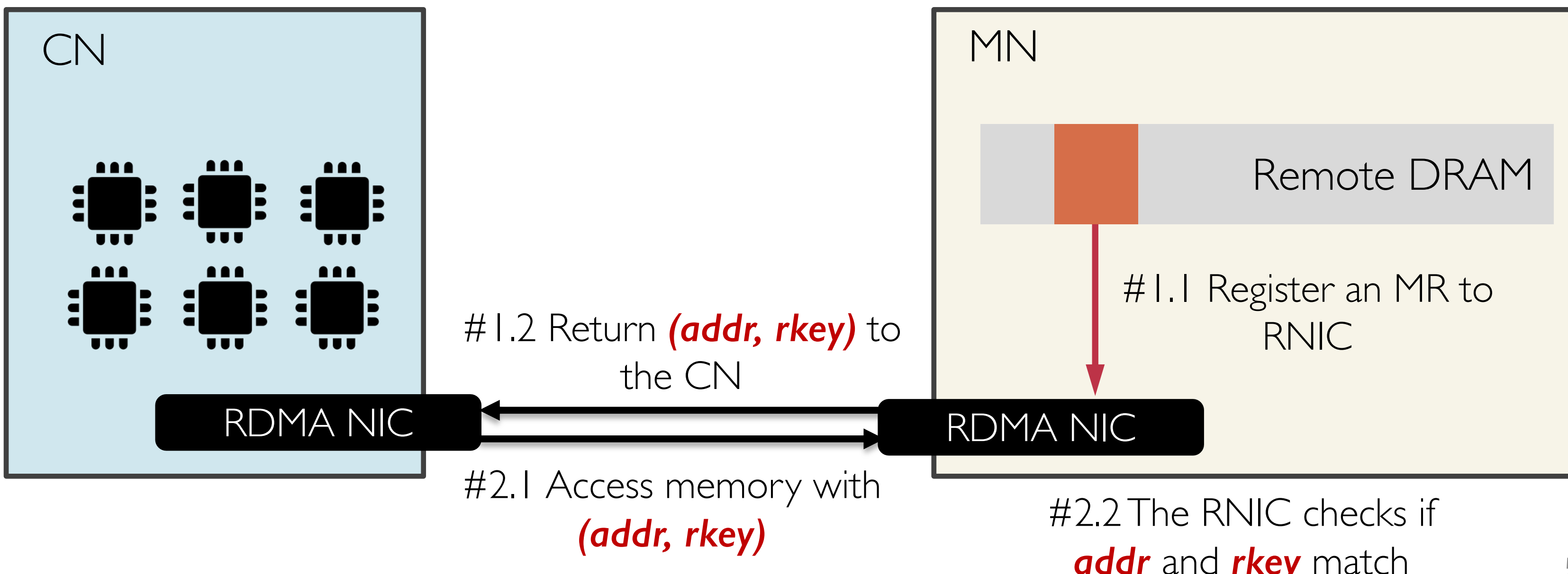

Existing Memory Management Approaches

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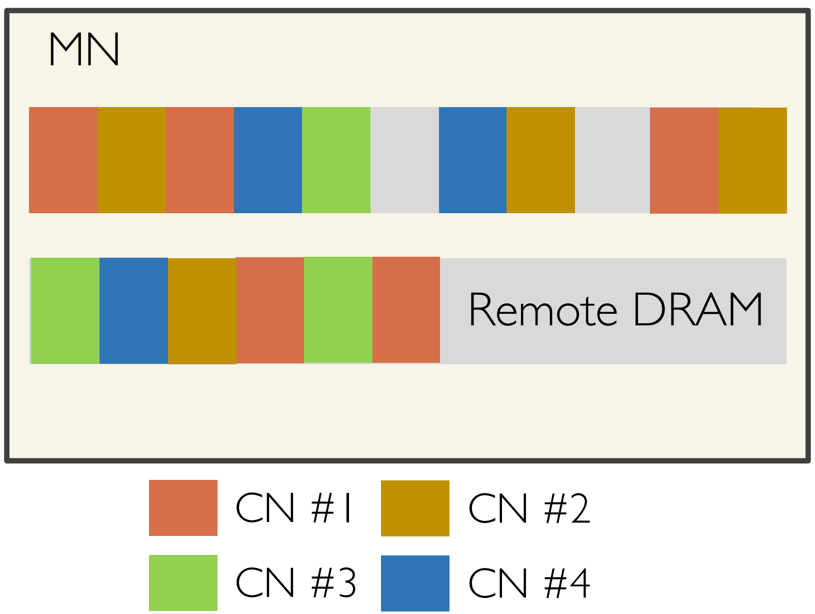

Pro:* *High memory utilization* *due to fine allocation granularity.

Limitation:* *Poor Performance

- ***frequent allocation requests***
- ***time-consuming MR registration***
- ***wimpy MN CPU***

Existing Memory Management Approaches

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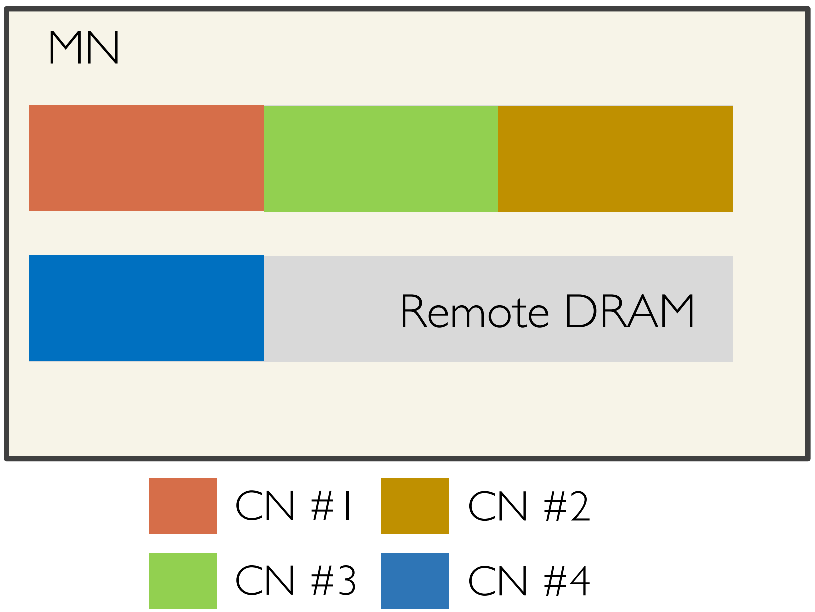

***Pro:** High performance due to few (or no) allocation requests during runtime*

***Limitation:** Poor memory utilization due to severe internal fragmentation.*

Existing Memory Management Approaches

- **Existing approaches cannot achieve *high-performance, high memory utilization, and no MN CPU usage* at the same time.**

Goals

#1 Fine-grained memory management for ***high memory utilization***

#2 Fast data-path memory allocation for ***high performance***

#3 No MN CPU usage to realize ***full disaggregation***

Opportunity – RNIC Offloading

- **Feature #1: Event-based work request triggering.**

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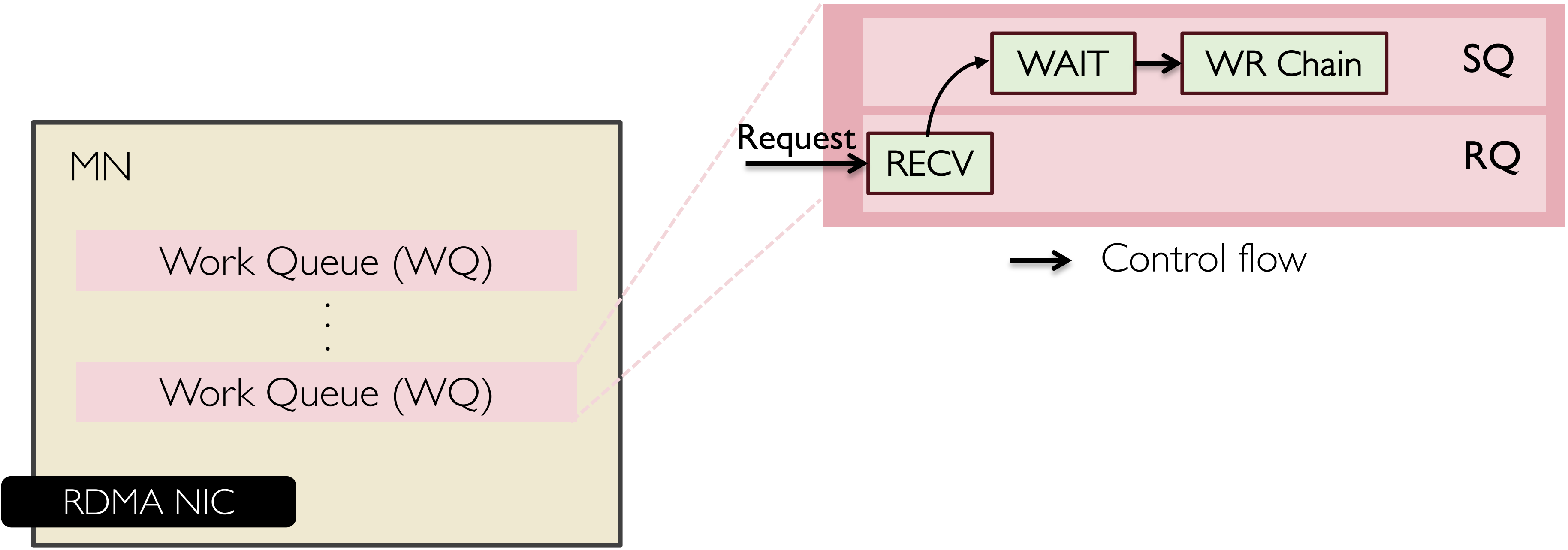

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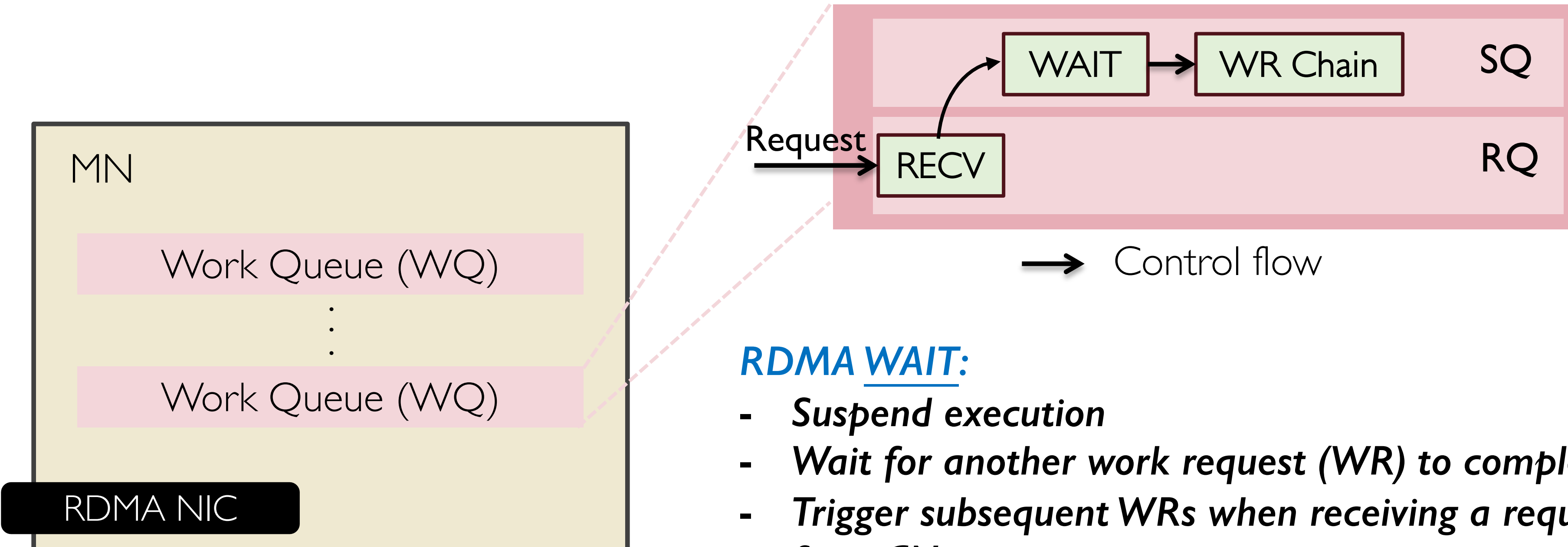

RDMA WAIT:

- ***Suspend execution***
- ***Wait for another work request (WR) to complete***
- ***Trigger subsequent WRs when receiving a request from CNs***

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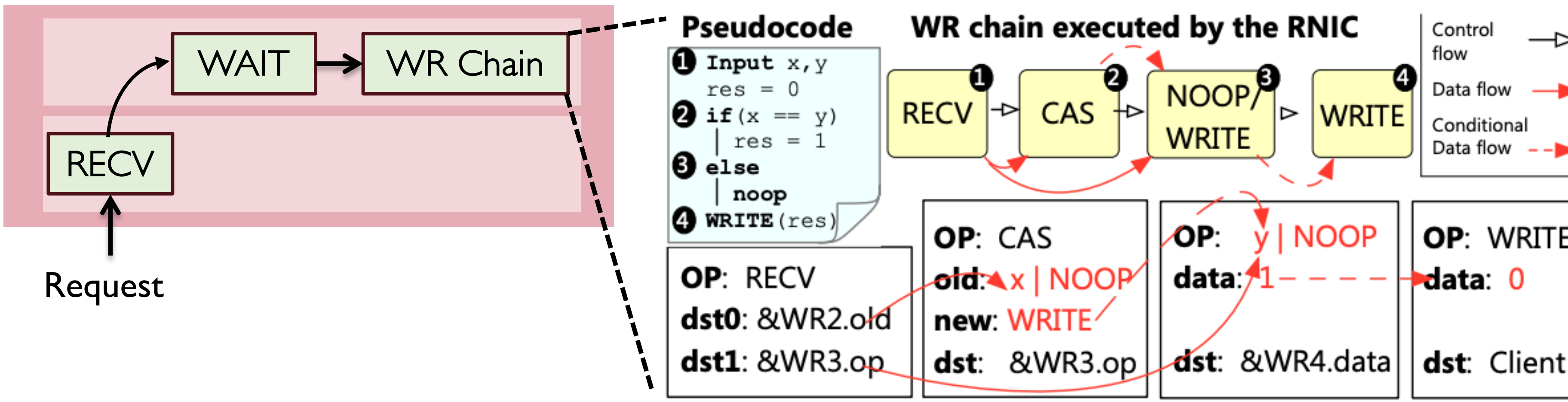

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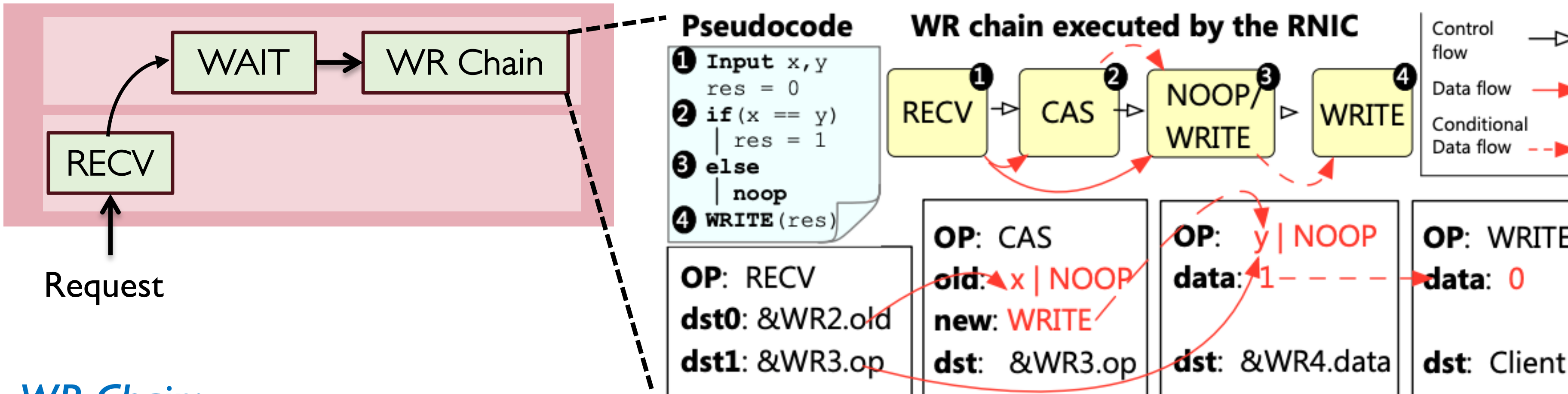


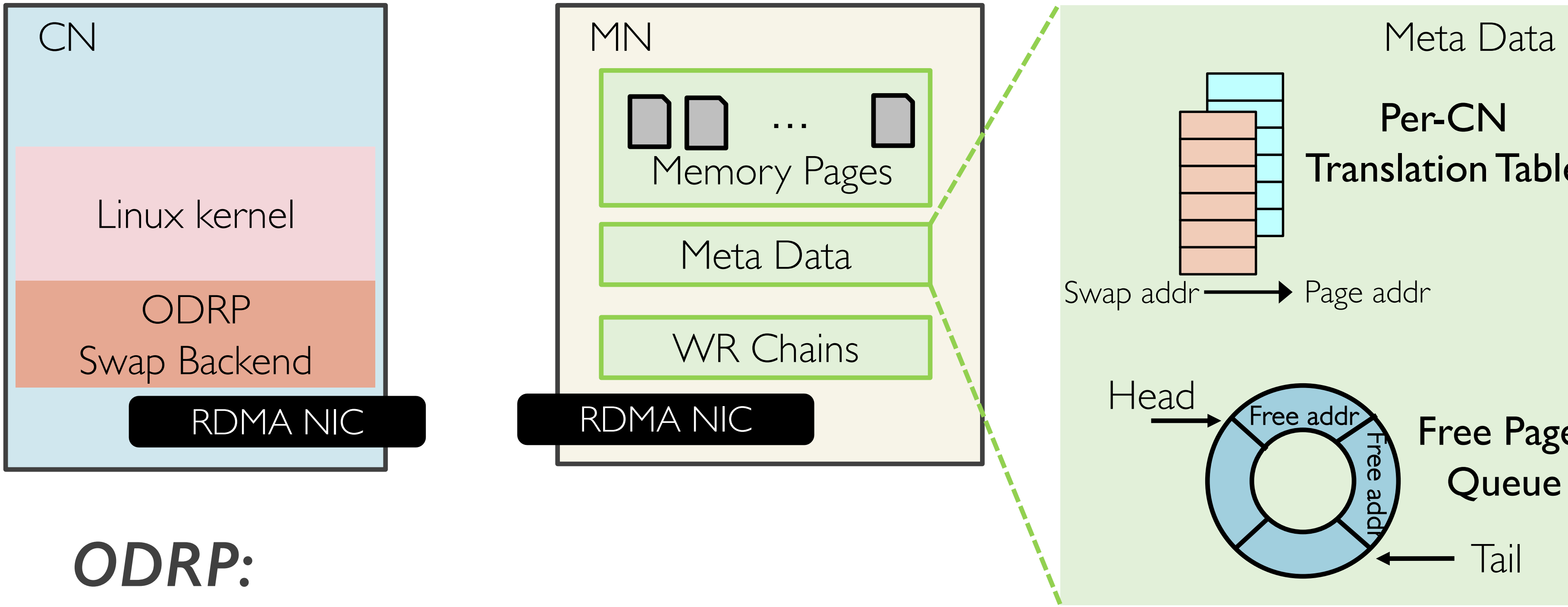
WR Chain:

- *Chain basic WRs (e.g., READ/WRITE) together*
- *Enable one-sided operations with richer semantics*

Opportunity – RNIC Offloading

Offload memory management logic to MN's RNIC.
CNs can *efficiently* allocate memory in the data path *on demand*!

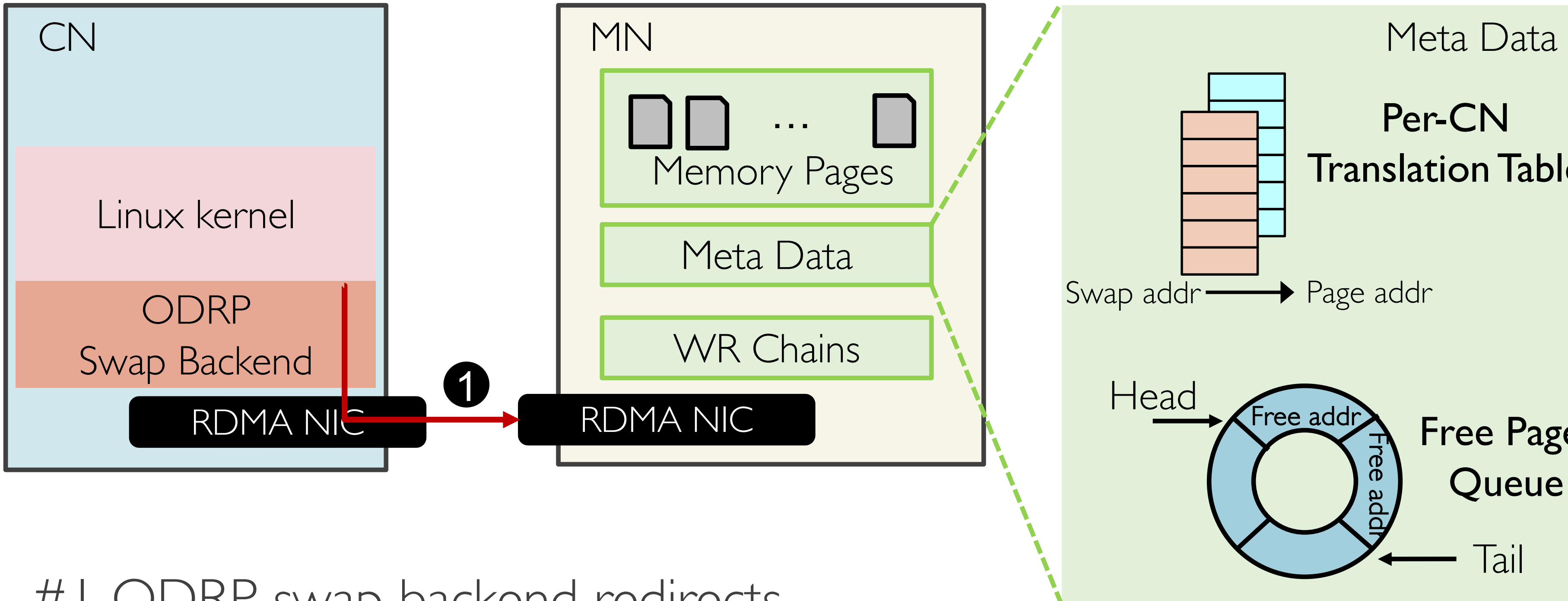
Design – Overview



ODRP:

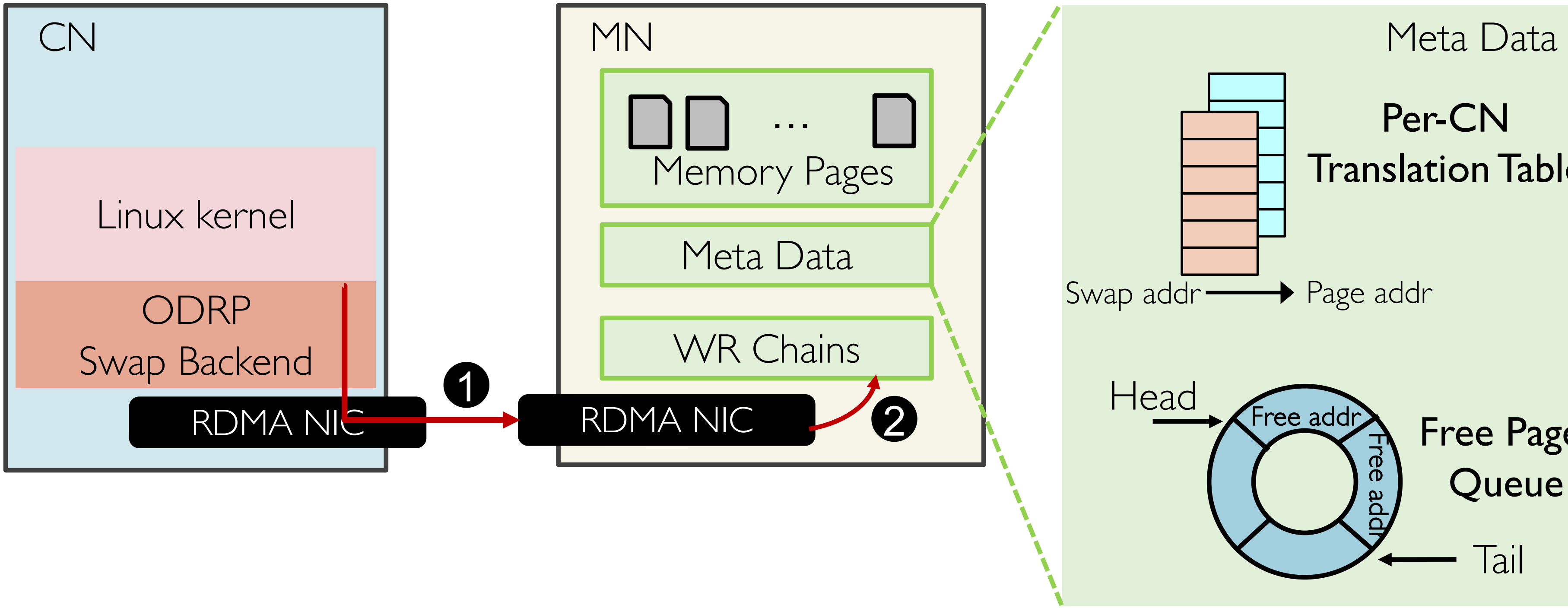
- *a swap-based system*
- *offload memory management logic to RNIC*

Design – Workflow



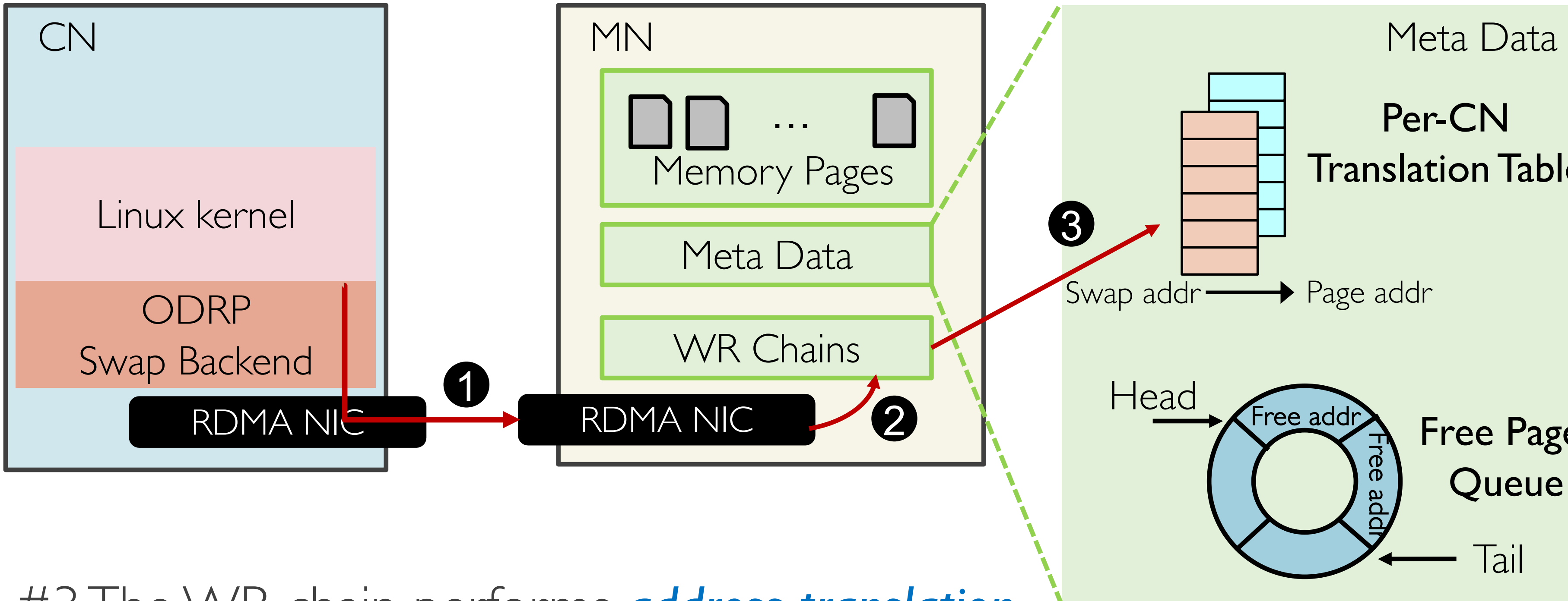
#1 ODRP swap backend redirects CNs' swap requests to the MN with RDMA SEND.

Design – Workflow



#2 The MN's RNIC then fetches and executes a WR chain.

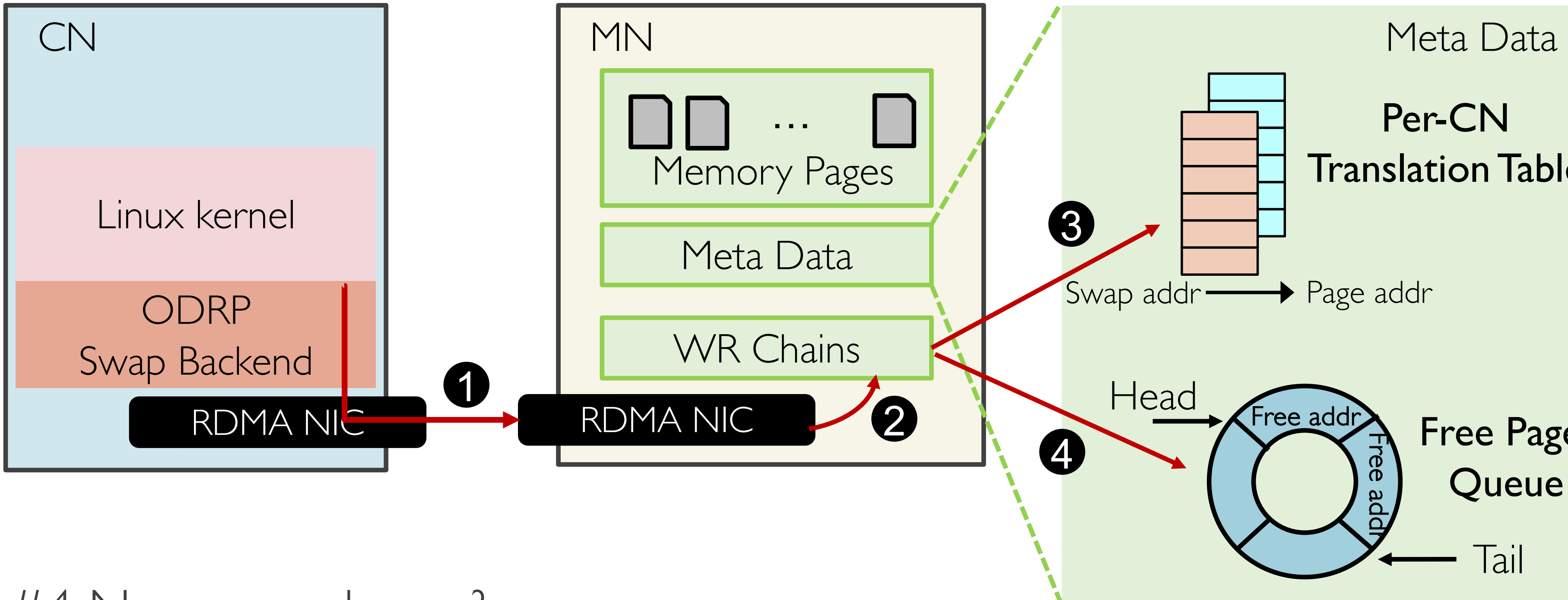
Design – Workflow



#3 The WR chain performs ***address translation***.

i.e. RDMA READ the translation table entry

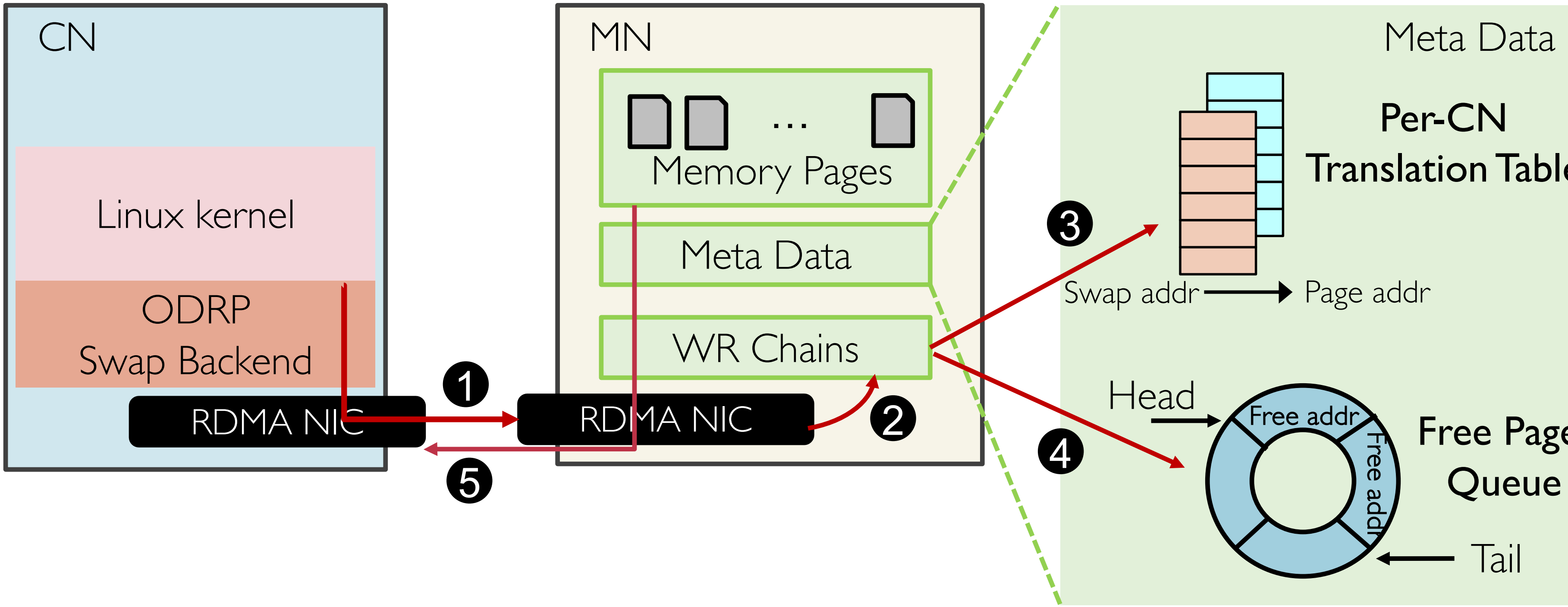
Design – Workflow



#4 No mapped page?

- *allocate* a page from Free Page Queue (i.e., RDMA FAA on Head)
- *update* the CN's translation table (i.e., RDMA WRITE the table entry)

Design – Workflow



#5 The WR chain reads/writes the memory page and returns the result.

Efficiency Challenge

- **C#1: Efficiency**
  - Complex logic requires ***longer WR chain → slower execution***.
  - How to minimize the number of WRs per chain?

Technique: CN-Assisted Principle

- **Shift part of the computation to CNs**
  - Observation #1: the base address of a CN's translation table can be shared with the CN securely.
  - Compute nodes directly provide the translation table entry address.

  - Observation #2: The CN knows whether a swap address is mapped.
  - The CN triggers different WR chains based on whether the swap address is mapped.
  - Avoid complex and time-consuming page fault detection in the WR chain.

Functionality Challenge

- **C#1: Efficiency**
  - Complex logic requires ***longer WR chain → slower execution***.
  - How to minimize the number of WRs per chain?

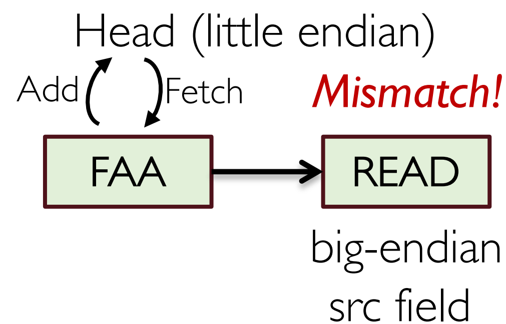
- **C#2: Functionality**

Functionality Challenge

- **Lack of modulo support**
  - Ring buffer necessitate modulo operation (%).
  - RDMA WRs *lack support for modulo operation* (%).

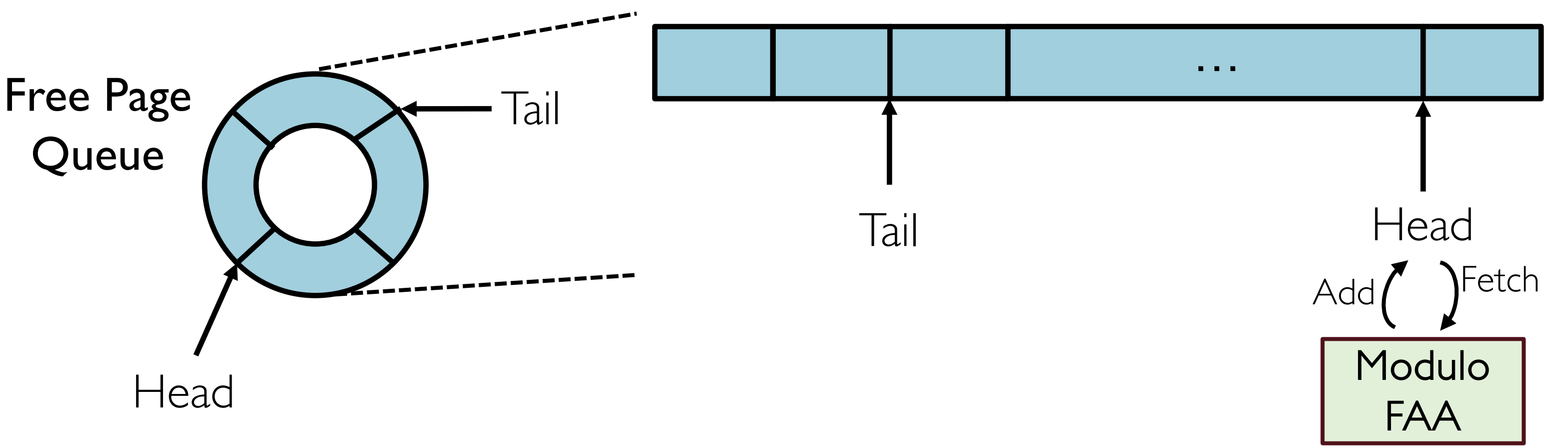
Functionality Challenge

- **Lack of modulo support**
  - Ring buffer necessitate modulo operation (%).
  - RDMA WRs *lack support for modulo operation* (%).
- **Mismatch in endianness**
  - FAA operates on little-endian values.
  - READ assumes a big-endian *src* field.



Technique: Meta WR

- **Meta WR #1: Fetch and Add with modulo support**
  - Observation: RNICs support an advanced WR – Masked Fetch and Add.
  - Mask the upper bits of the value to achieve ModuloFAA.



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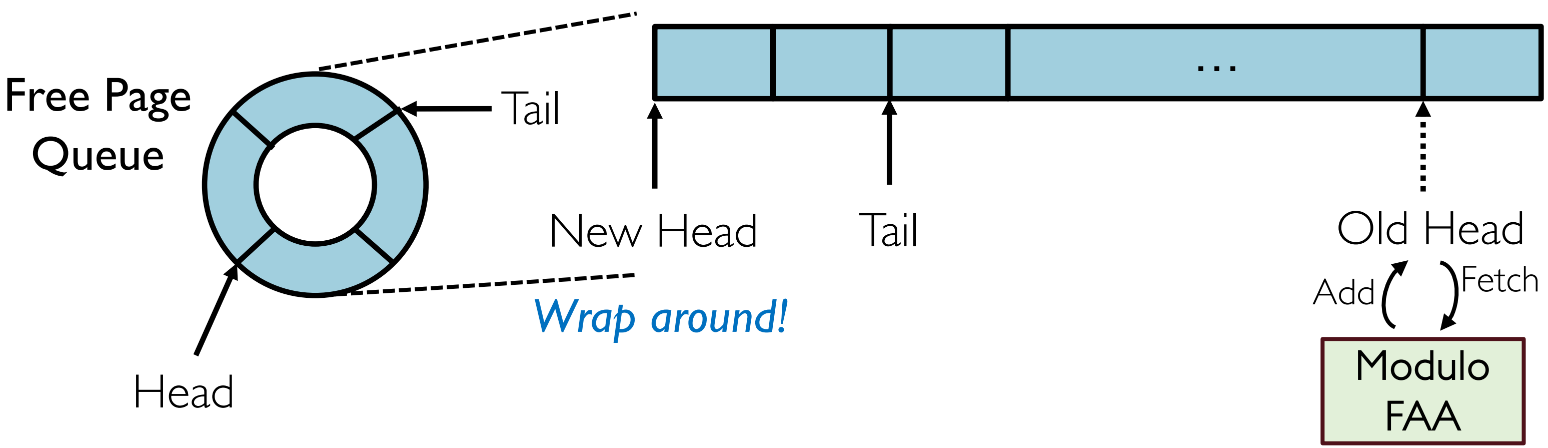
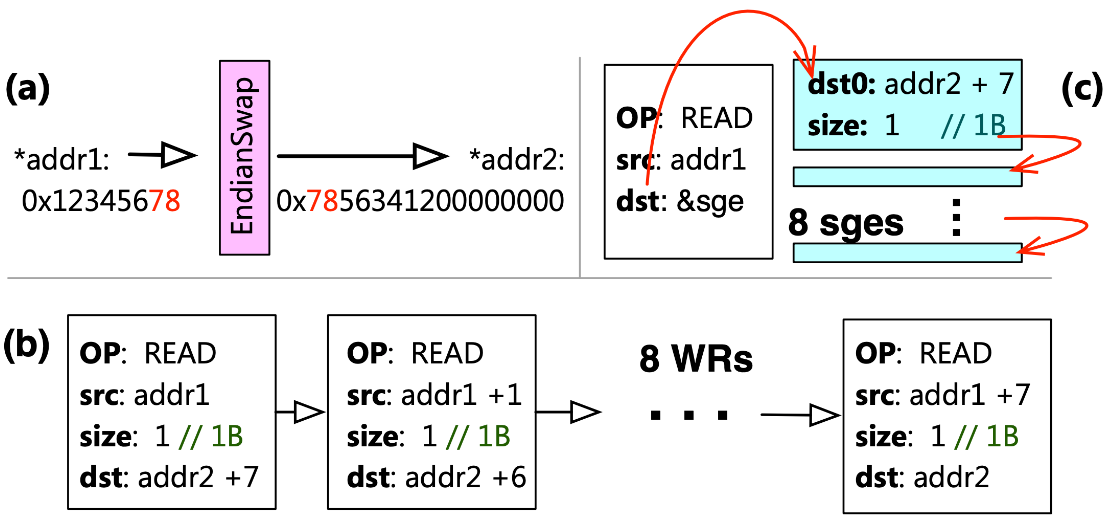
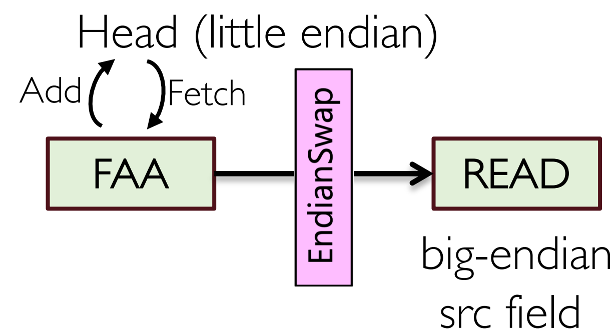


Technique: Meta WR

- **Meta WR #2: EndianSwap**
  - **Observation:** RNICs support scatter-gather I/O.
  - One RDMA READ to convert endianness.



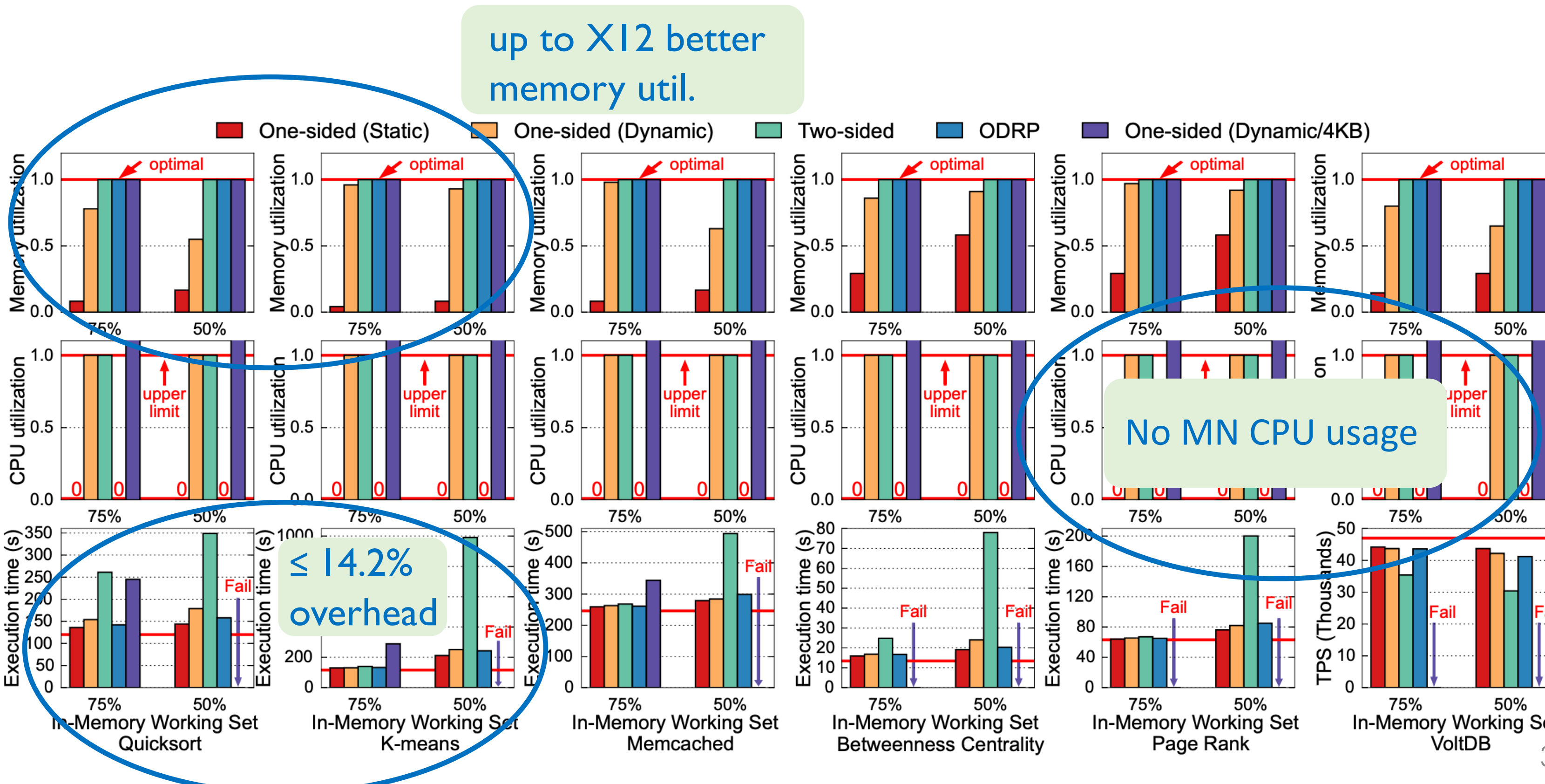


Experimental Setup

- **Harward Setup**
  - **CPU:** 12-Core Intel Xeon E5-2650 CPU
  - **DRAM:** 128 GB DDR4 RAM
  - **RNIC:** 100 Gbps Mellanox ConnectX-5 RNIC
  - **Cluster:** 8 CNs (12 GB swap space), 1 MN (only use one CPU core)
- **Other baselines**
  - **One-sided(Static):** pre-registering MR with the size of the CN's swap space
  - **One-sided(Dynamic):** registering and allocating 1MB MR on demand
  - **Two-sided:** using RPC in the data path

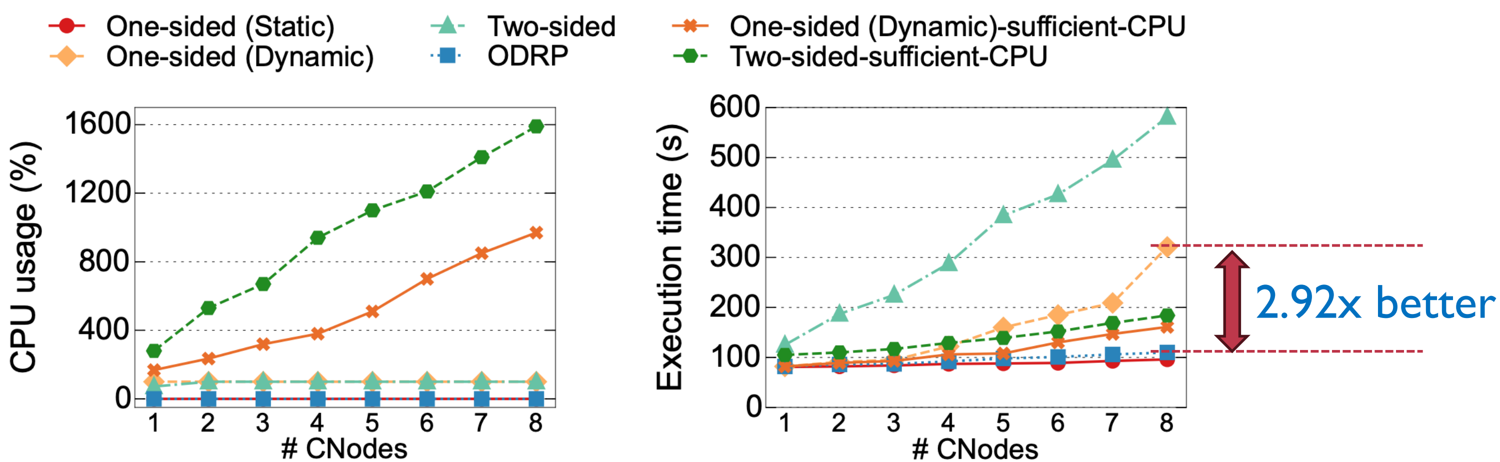
Application Benchmark

- Run real-world workloads on 8 CNs.



Scalability

- Can ODRP scale as the number of CNs increases?



ODRP can prevent the weak MN CPU from becoming a bottleneck.

- less than 14.6% performance overhead compared to One-sided(Static)
- 2.92x better performance than one-sided(Dynamic)

Conclusion

- Current DM systems cannot achieve high memory utilization, zero MN CPU usage, and high performance at the same time.
- We propose ODRP, the first system that leverages RNIC offloading to achieve
  - ideal memory utilization
  - zero MN CPU usage (i.e., true disaggregation)
  - high performance
- We introduce two software techniques to address the efficiency and functionality challenges of RNIC offloading.
- ODRP significantly improves memory utilization with less than 14.6% performance overhead in real-world workloads.

Thanks!

Q&A