nuKSM: NUMA-aware Memory De-duplication on Multi-socket Servers

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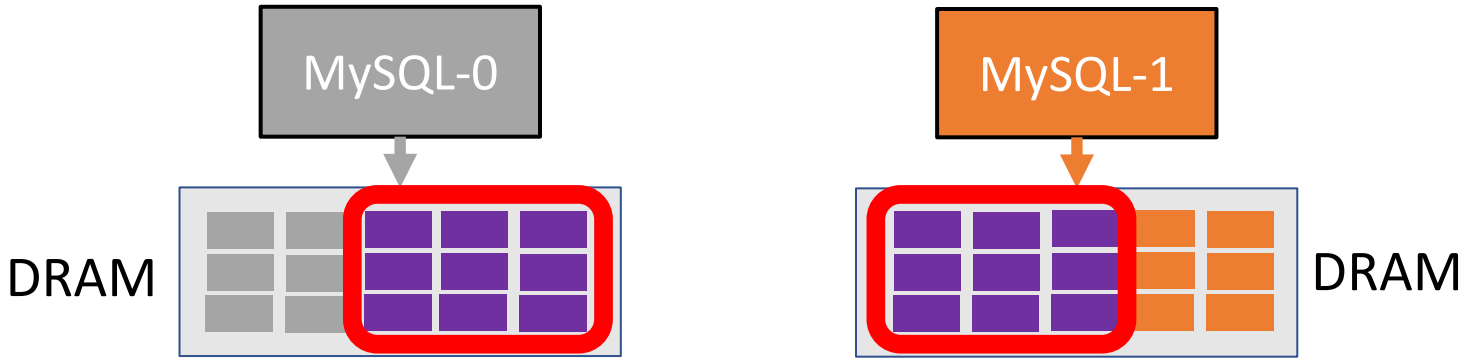
Executive summary

- Memory de-duplication (KSM in Linux) is NUMA-unaware
  - Uncontrolled performance variability
  - Subversion of process priority
- Our proposal: NUMA-aware KSM (nuKSM) in Linux
  - Judicious placement of de-duplicated pages to limit NUMA overheads
  - Priority-aware placement of de-duplicated pages
- Beyond NUMA: De-centralize KSM's data structures for scalability

De-duplication reduces memory consumption



- Identical content across multiple processes/VMs → Opportunity for memory consolidation
  - Similar applications, OS images, libraries, etc.

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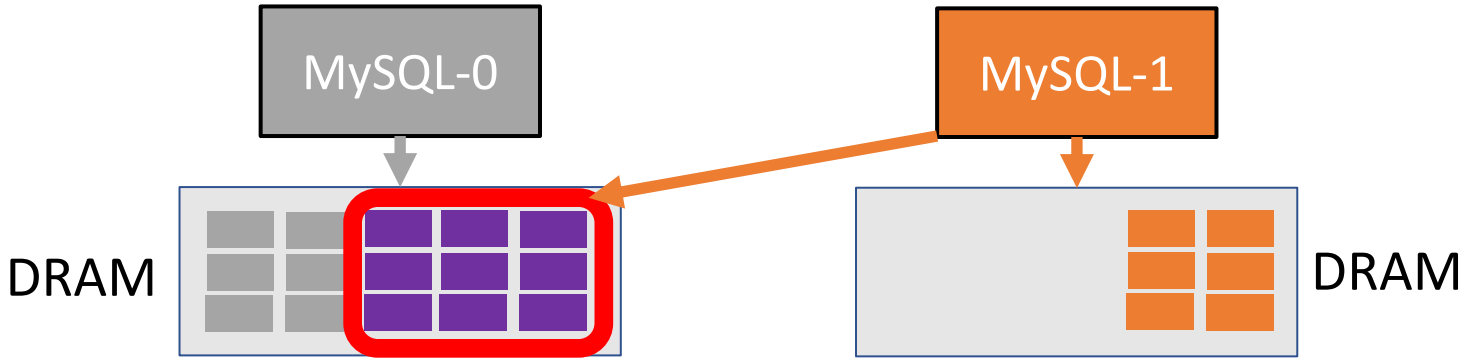

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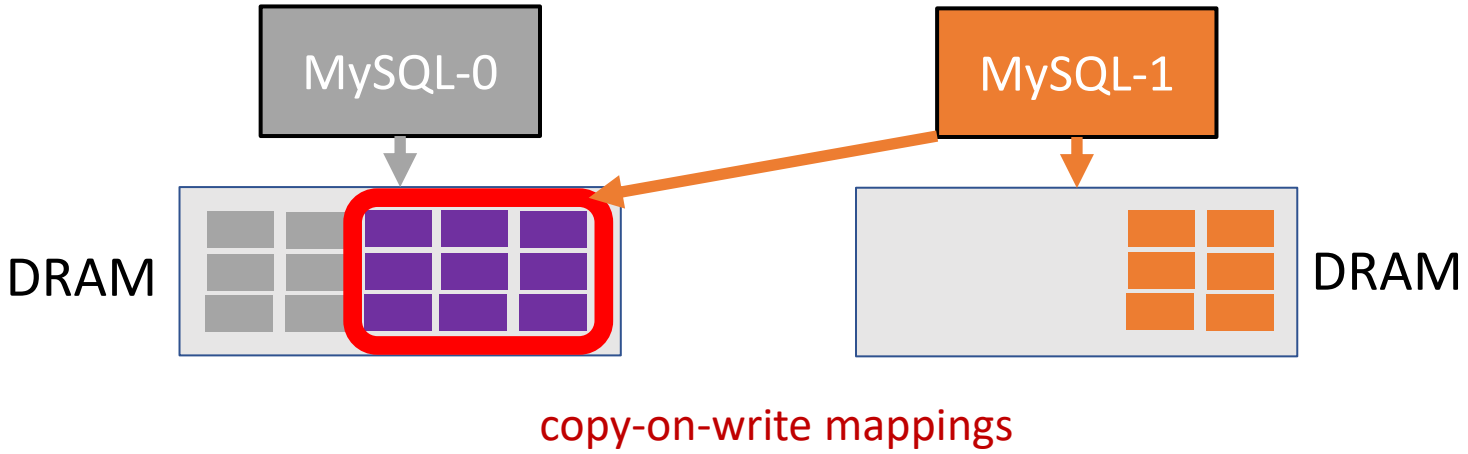
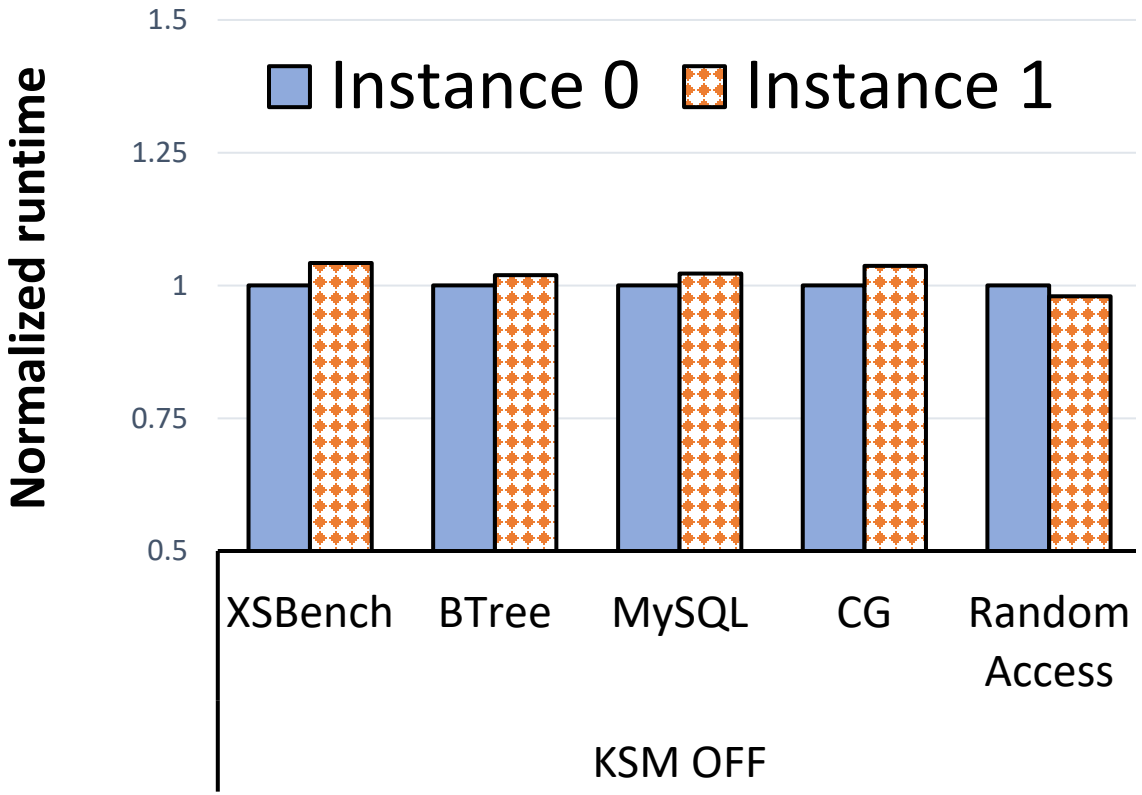


- Scan pages in physical memory
- Remove duplicate content using copy-on-write
  - Examples: Kernel same page merging (KSM) in Linux, VMware's Transparent Page Sharing (TPS)

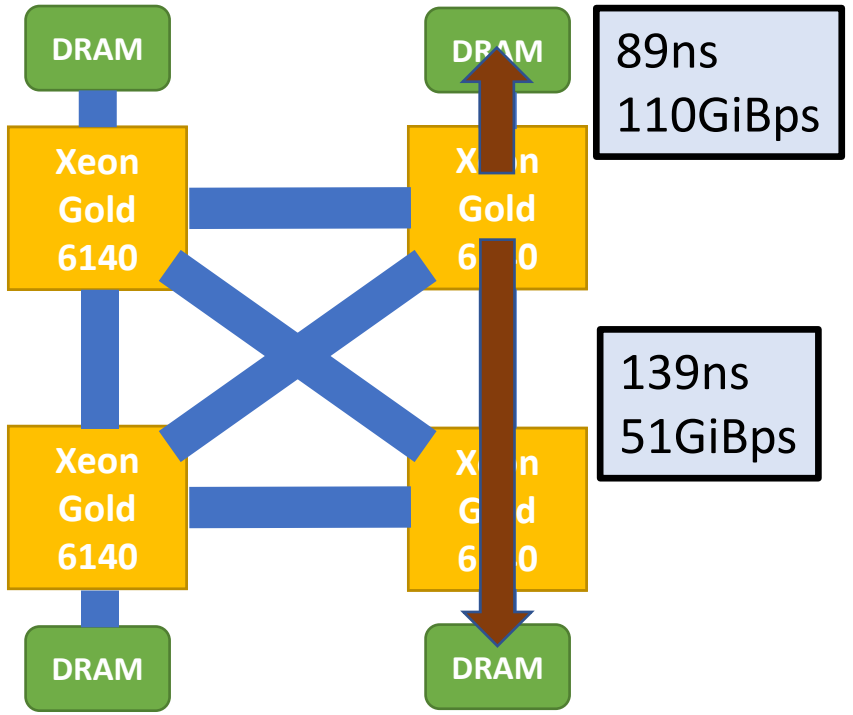
Observation 1: De-duplication introduces perf. variations



20-46% performance variation across instances of the same application!

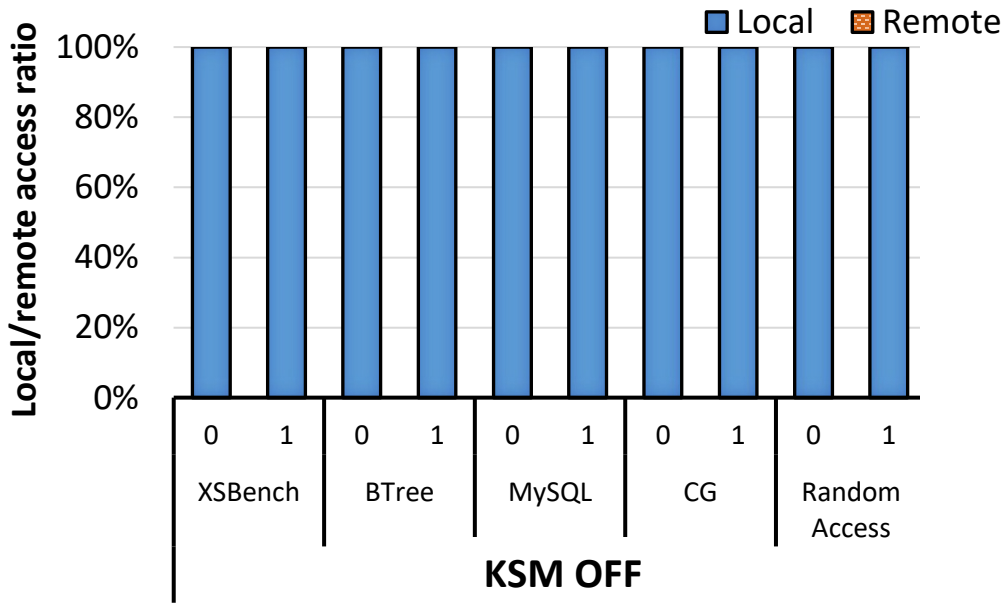
NUMA-ness in multi-socket servers

- Non-uniform memory access (NUMA) systems
  - Important for scaling memory capacity and bandwidth
  - Performance determined by access latency



Insight: De-duplication collides with NUMA

- Unbalanced local/remote memory access ratio across instances



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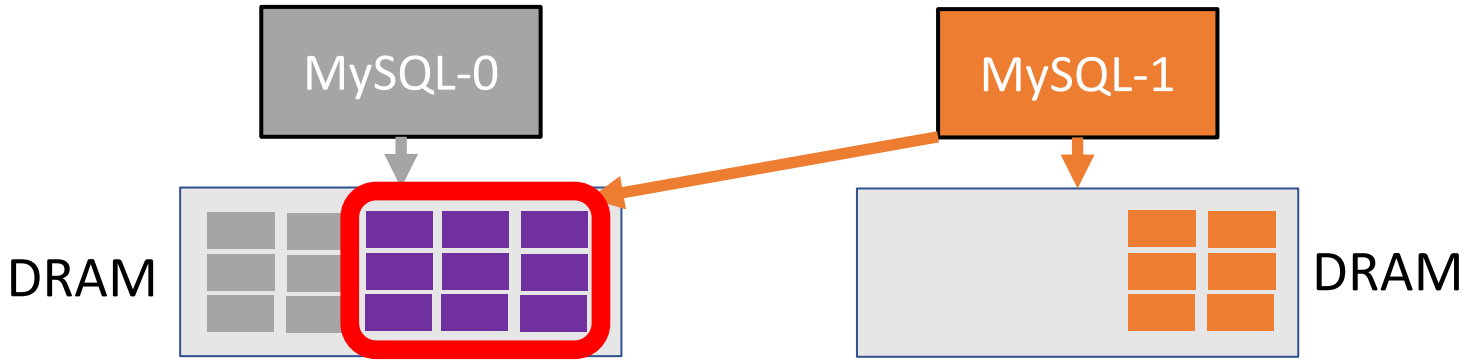
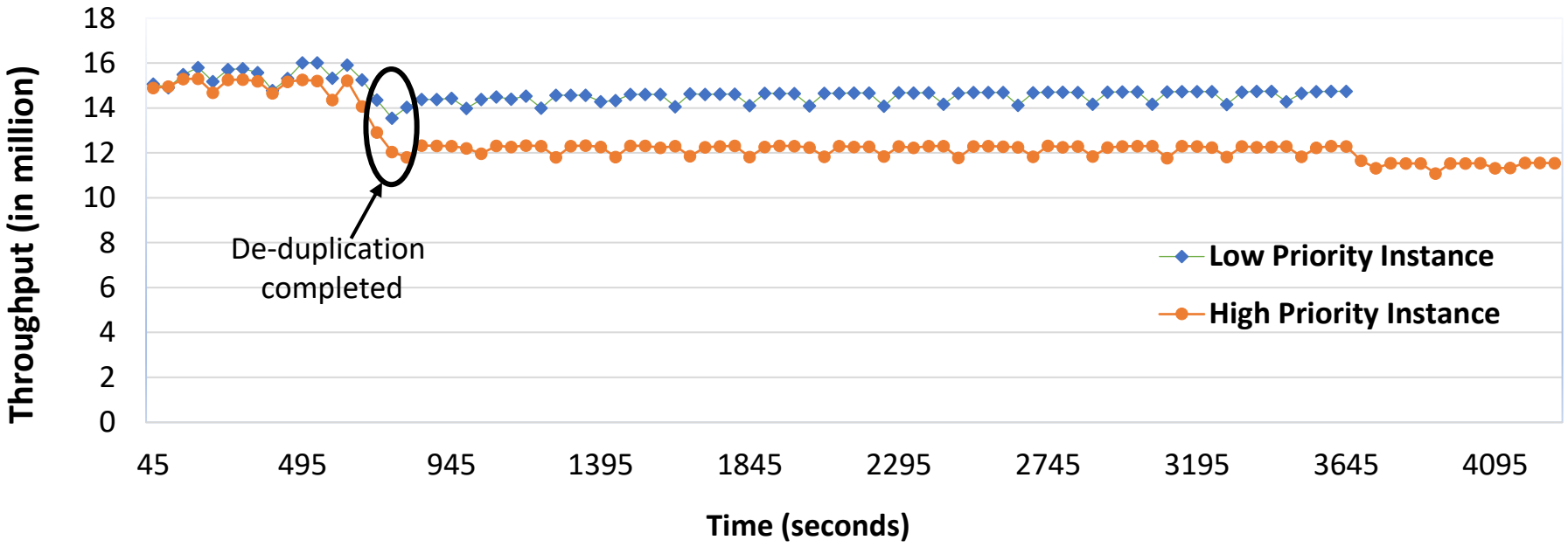


- Could have placed de-duplicated pages on Instance “1”’s local memory
- How does KSM decide where to place a merged page?
  - Rather arbitrary: Which ever process’s pages are scanned later
  - The order of scanning dictates page placement !

Observation 2: Subversion of priority goals



- High priority process may suffer high remote memory accesses
- No way to tune the system

Objective:

Enhance Linux's KSM (de-duplication) to contain performance variations and avoid priority subversion

Proposal:

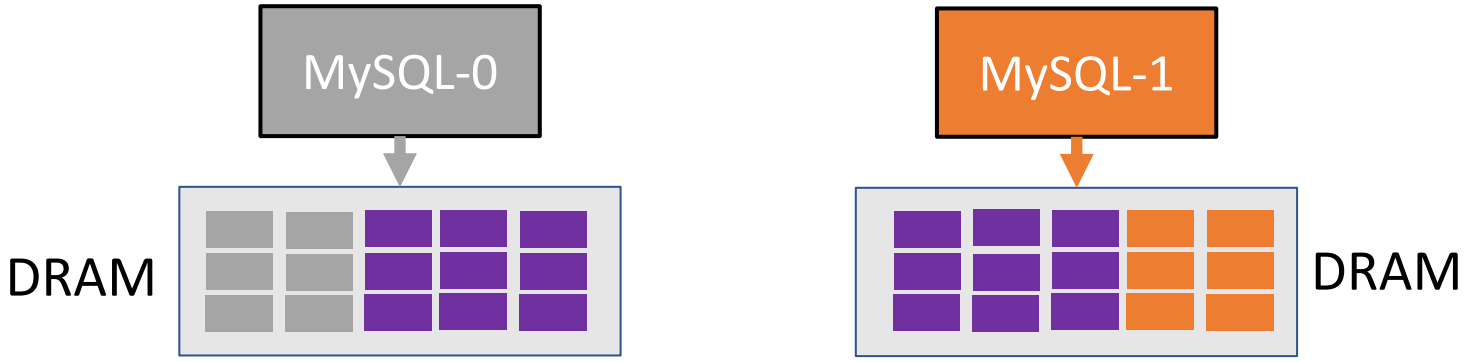
nuKSM: NUMA-aware Memory De-duplication on Multi-socket Servers

Code: https://github.com/csl-iisc/nuKSM-pact21-artifact

nuKSM: Judicious placement of de-duplicated pages

Idea: Place de-duplicated page on the node that accesses it more frequently

- Minimizes aggregate impact of remote accesses



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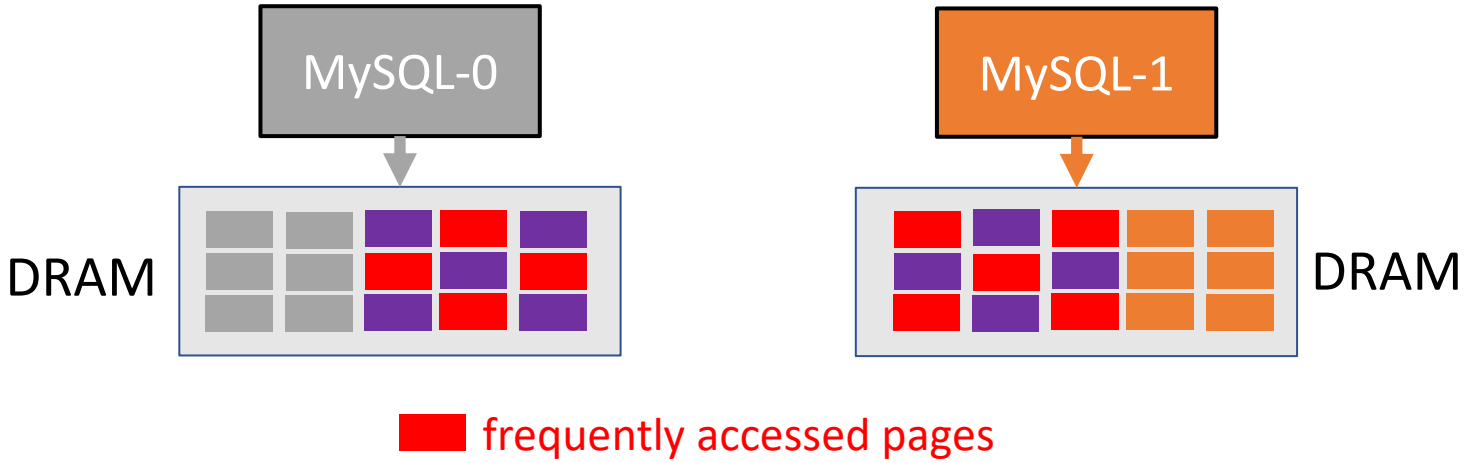

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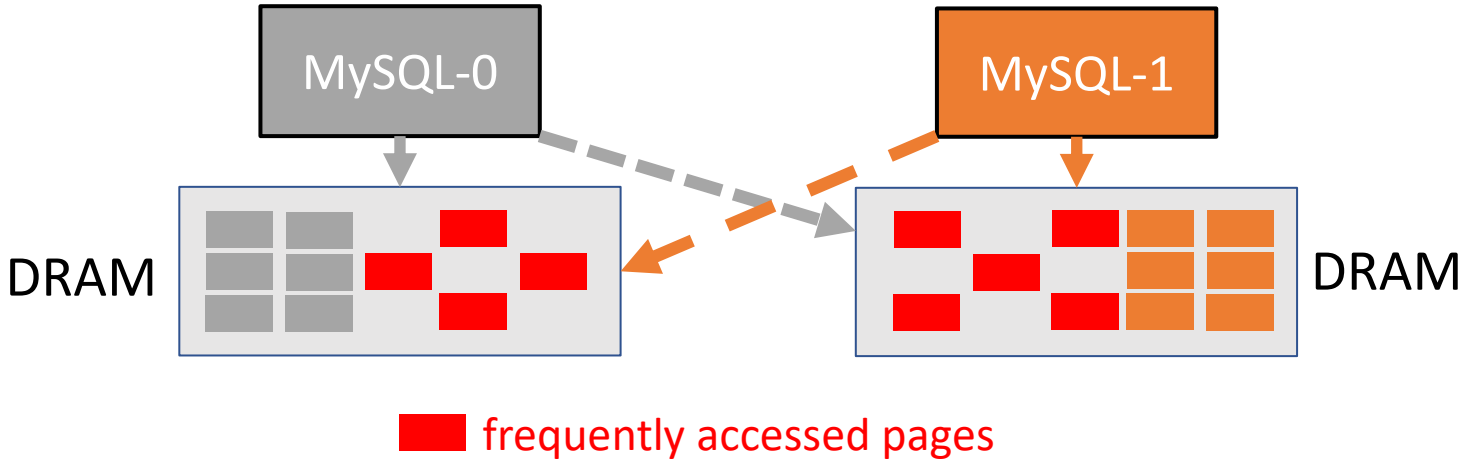

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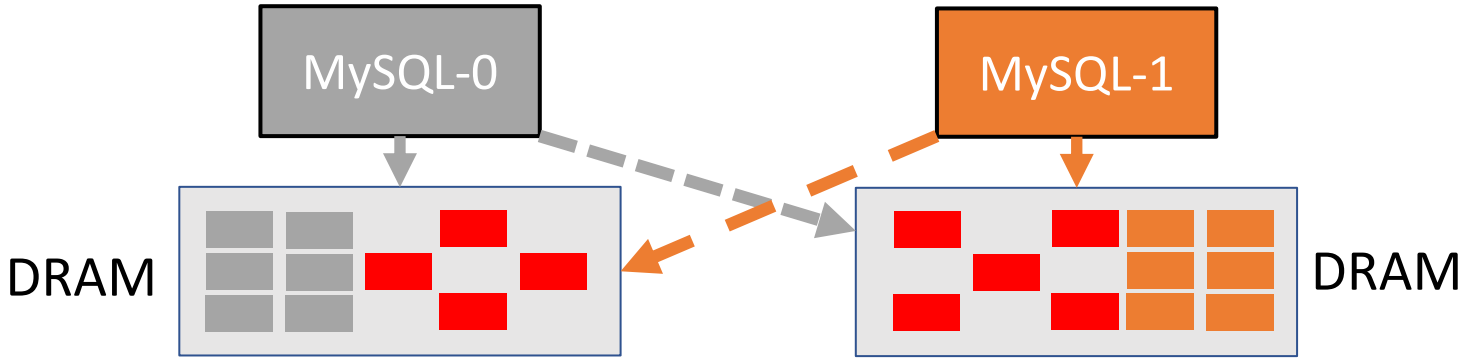
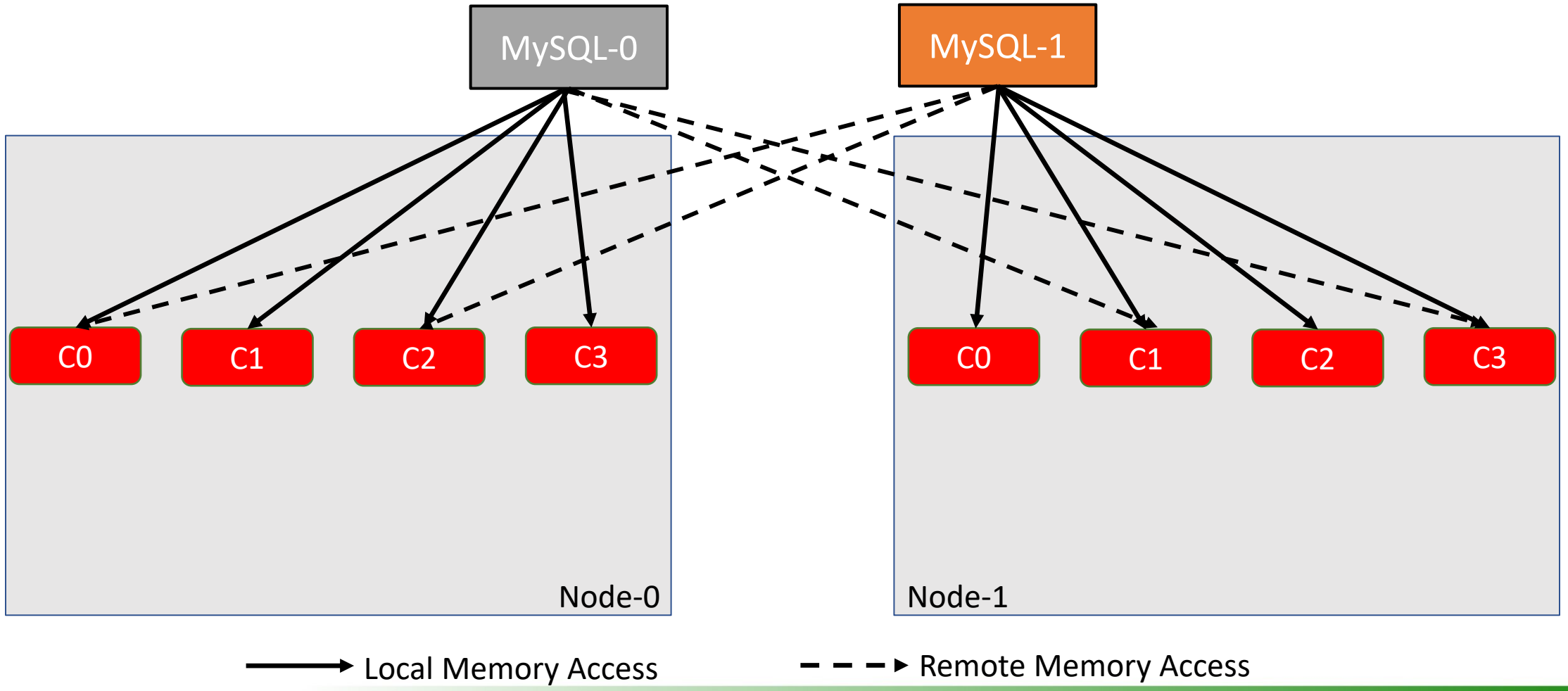


- **Challenge:** How to identify who accesses a page more frequently?
  - Repurpose Linux's **active** and **inactive** lists (originally for swapping)

nuKSM: Judicious placement of de-duplicated pages

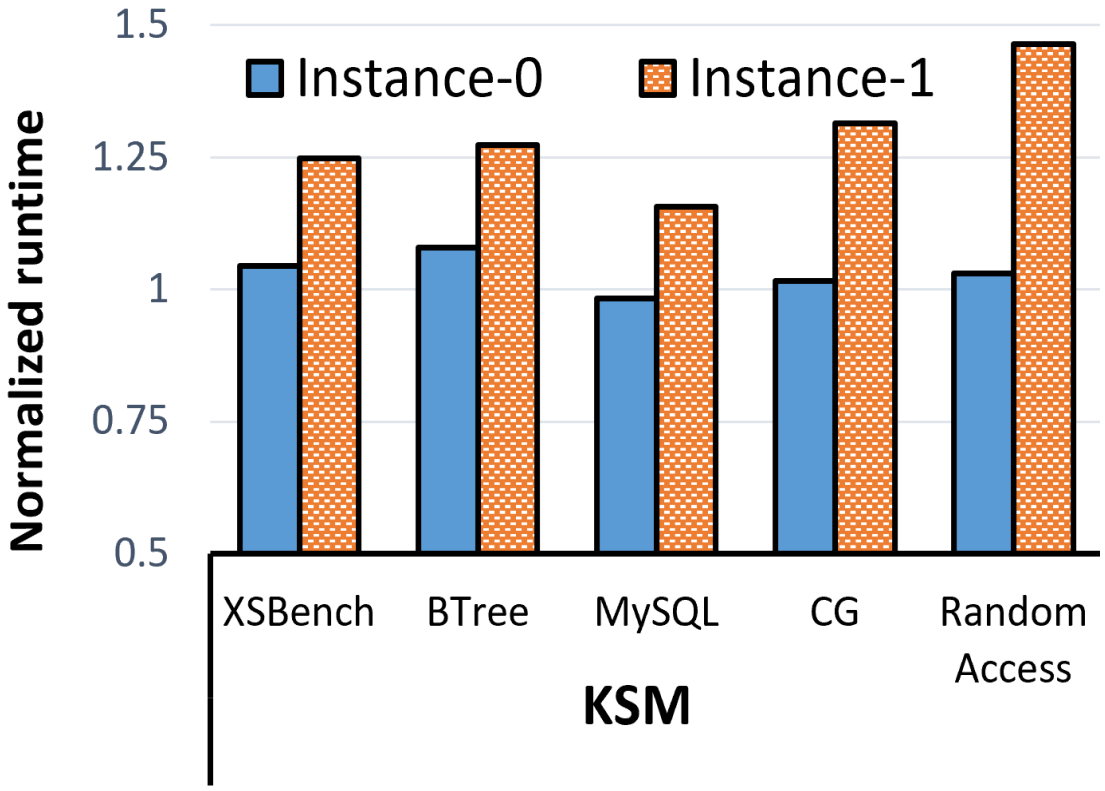


Evaluation Methodology

Hardware Platform	
Model	2-socket Intel Skylake
CPU cores	18 cores per socket @ 2.30GHz
Cache	25MiB shared L3 cache
Memory	DDR4-2666, 192GiB per socket

Workloads	
XSBench	11 GiB
MySQL	20 GiB
BTree	5.6 GiB
RandomAccess	2.8 GiB
CG	3.5 GiB

nuKSM avoids performance variations



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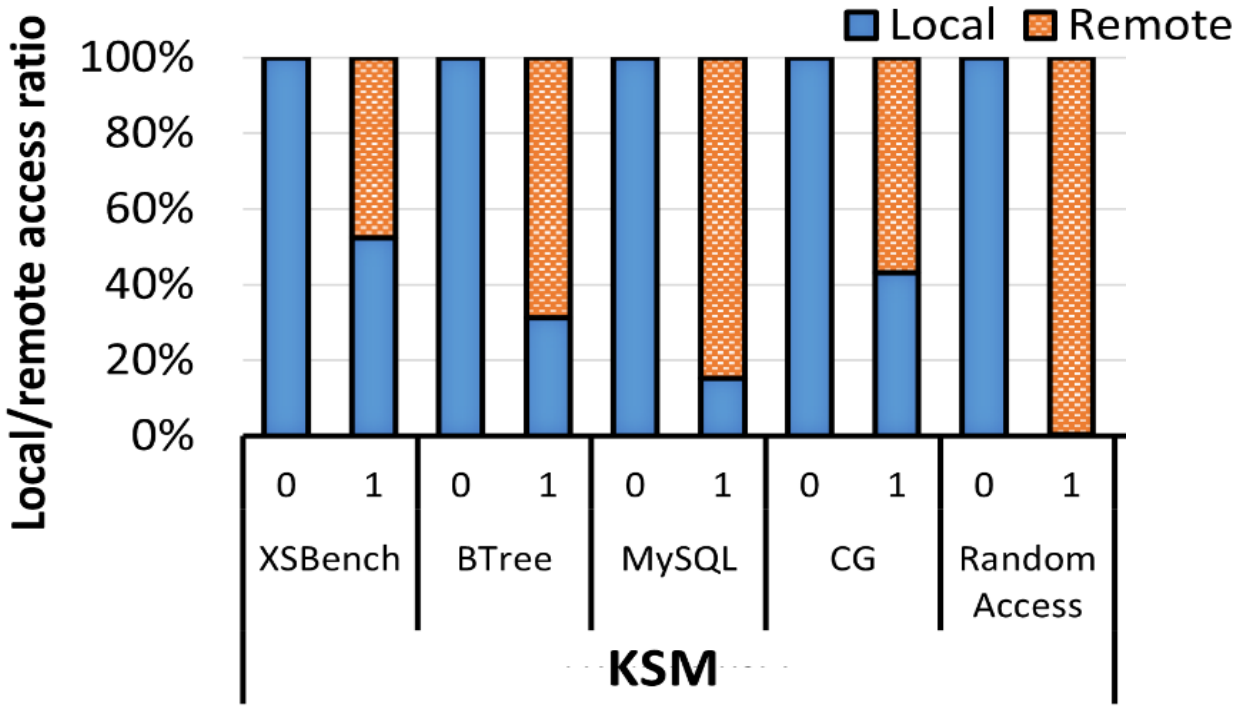


nuKSM avoids performance variations

Benchmark	Fairness *	
	KSM	nuKSM
XSBench	0.84	0.98
Btree	0.85	0.98
MySQL	0.85	0.99
CG	0.77	0.99
Random-Access	0.70	0.94

$$* \ Fairness\ (I0, I1) = \frac{\min(slowdown(Instance\ 0), slowdown(Instance\ 1))}{\max(slowdown(Instance\ 0), slowdown(Instance\ 1))}$$

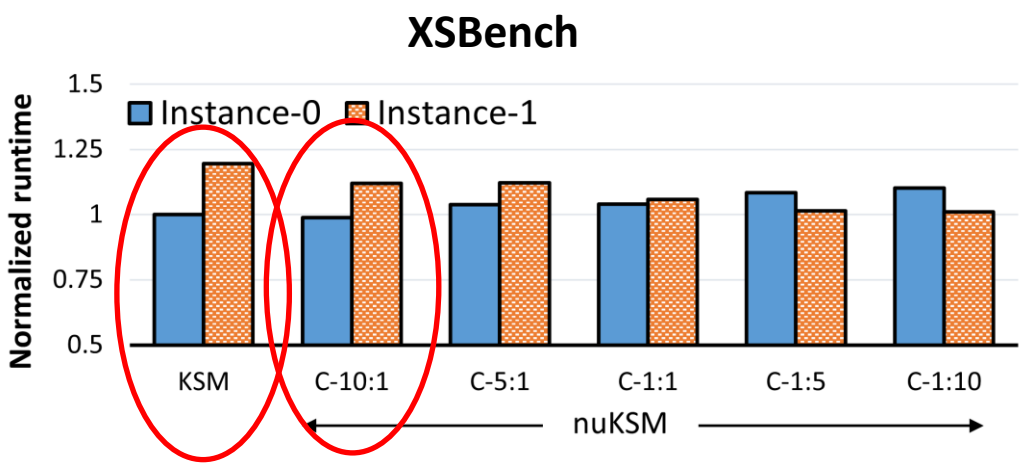
nuKSM: Priority based memory de-duplication

- Distribute NUMA overhead in proportion to priority ratios

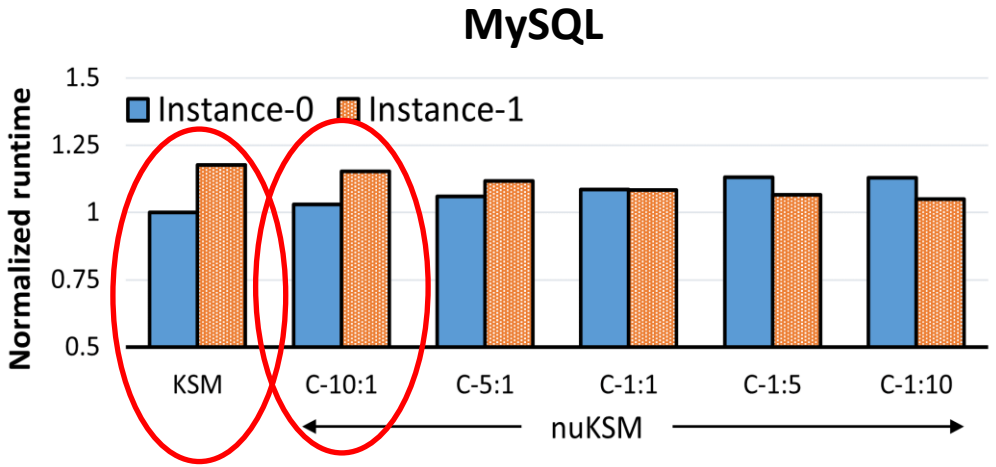
- Derive priority from Linux's *nice* values
  - -20 (highest priority) <= nice <= 19 (lowest priority)
  - *snice (scaled nice)* = nice + 21

- $nushare^{(p)} = 1 - \frac{snice(current)}{\sum_{tasks\ using\ p} snice(task)}$

Priority based memory de-duplication

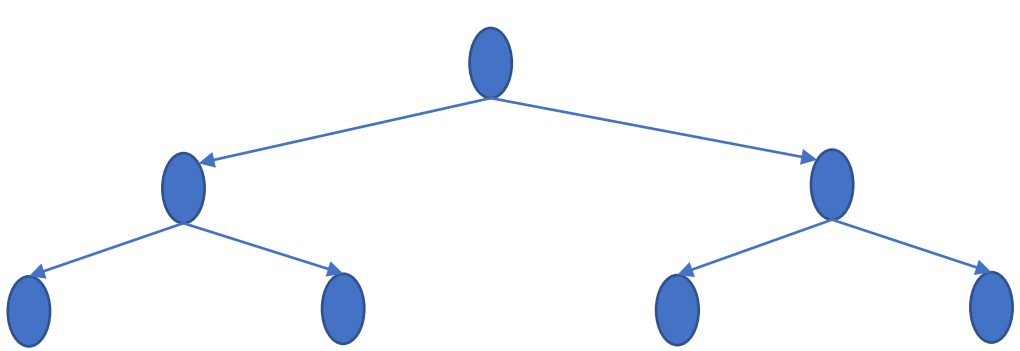


Priority of Instance-0 decreases
Priority of Instance-1 increases

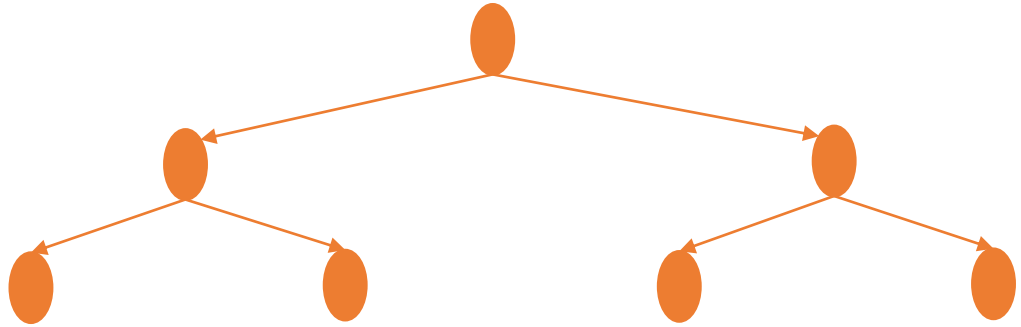


Priority of Instance-0 decreases
Priority of Instance-1 increases

Beyond NUMA: Scaling KSM to larger memory sizes



Stable Tree



Unstable Tree

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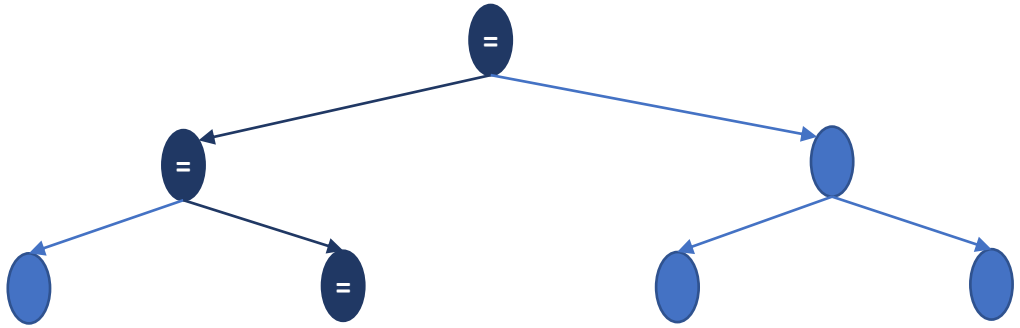

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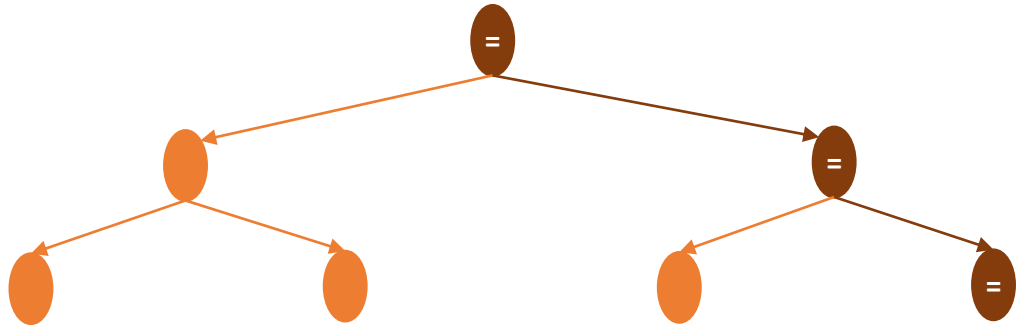
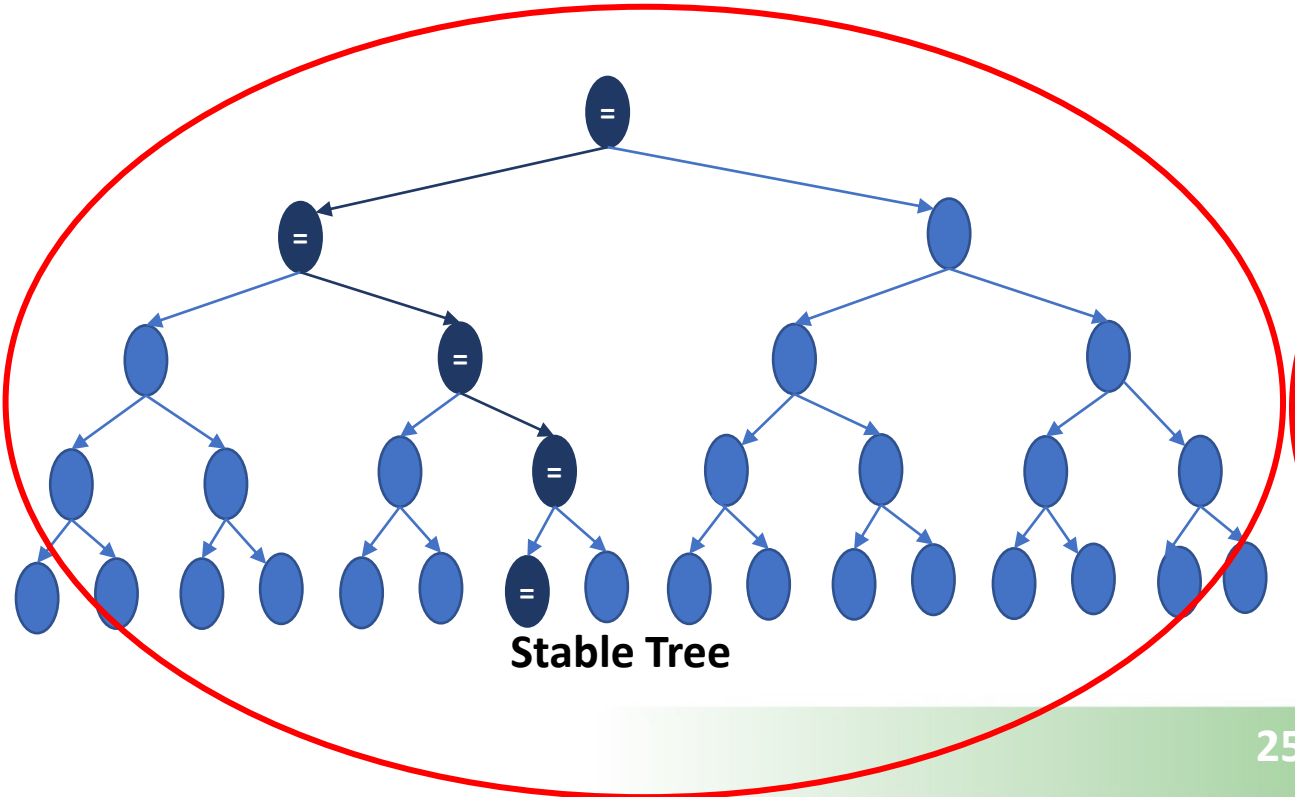
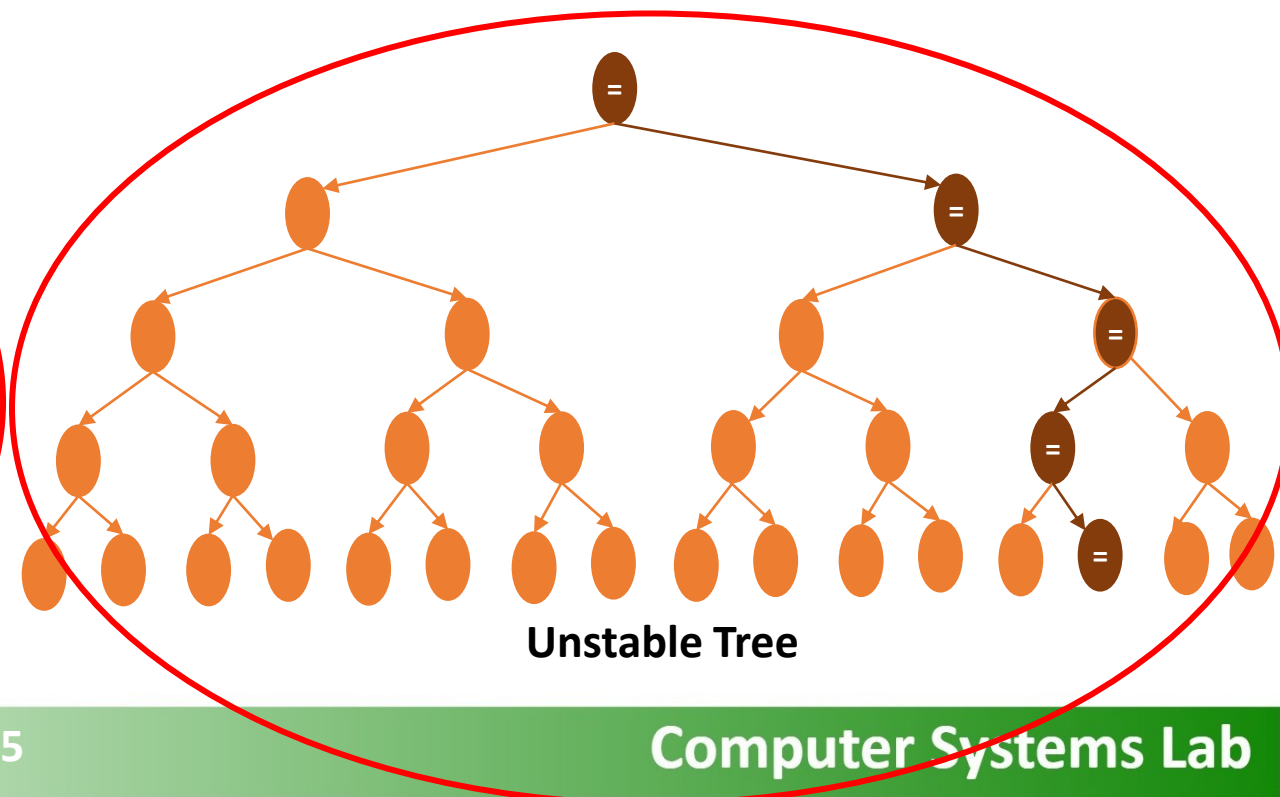


Unstable Tree

Beyond NUMA: Scaling KSM to larger memory sizes

Centralized data structures





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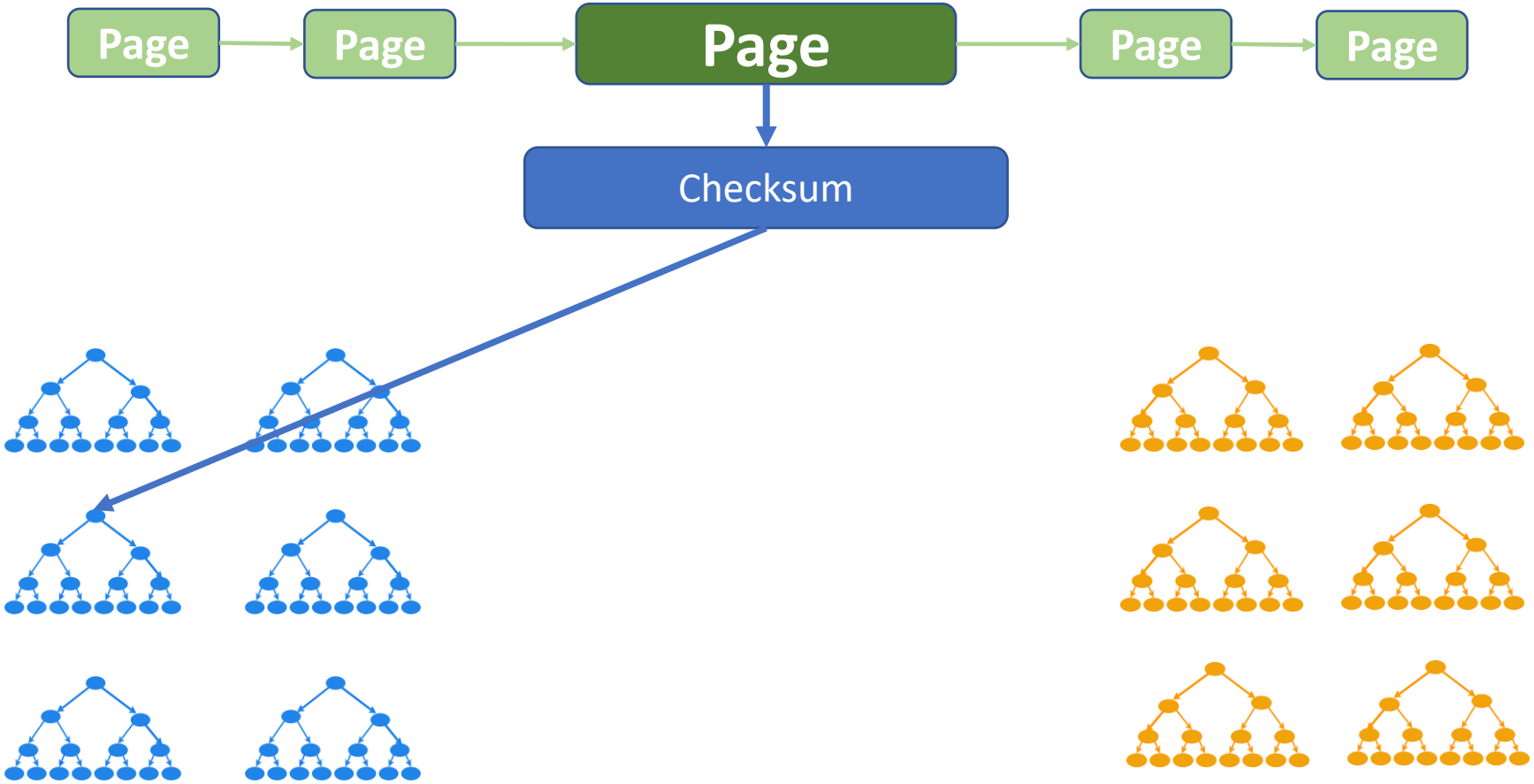

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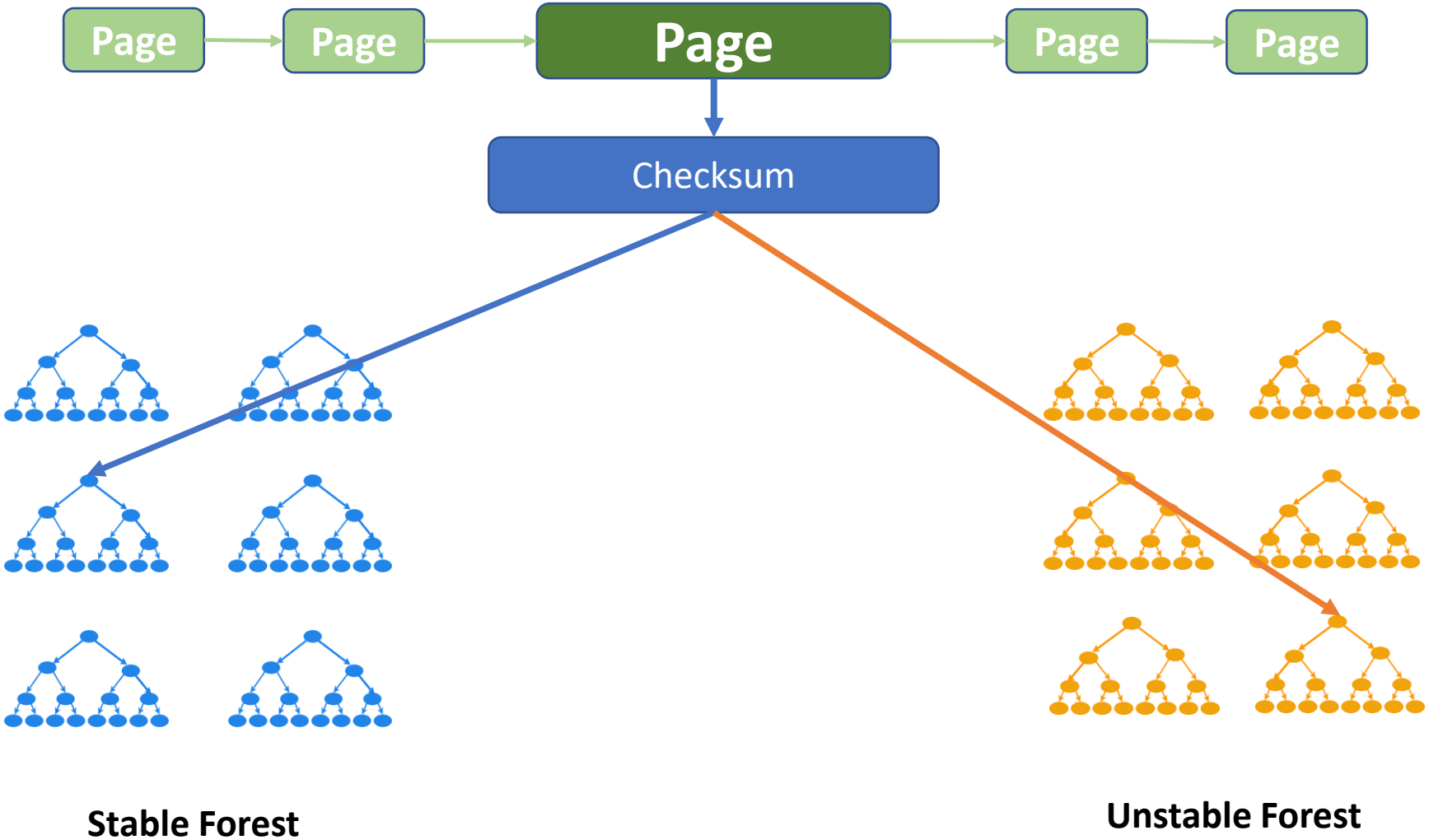

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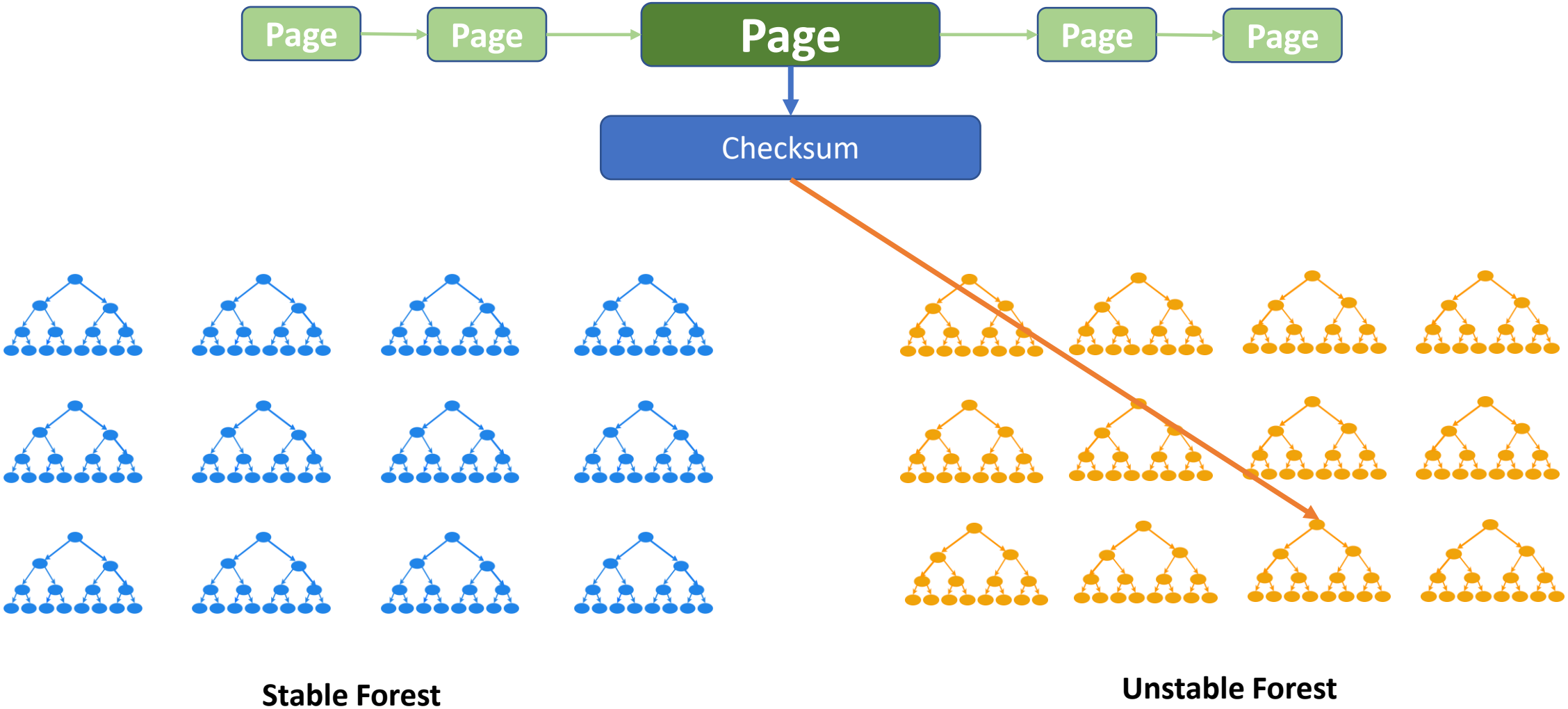
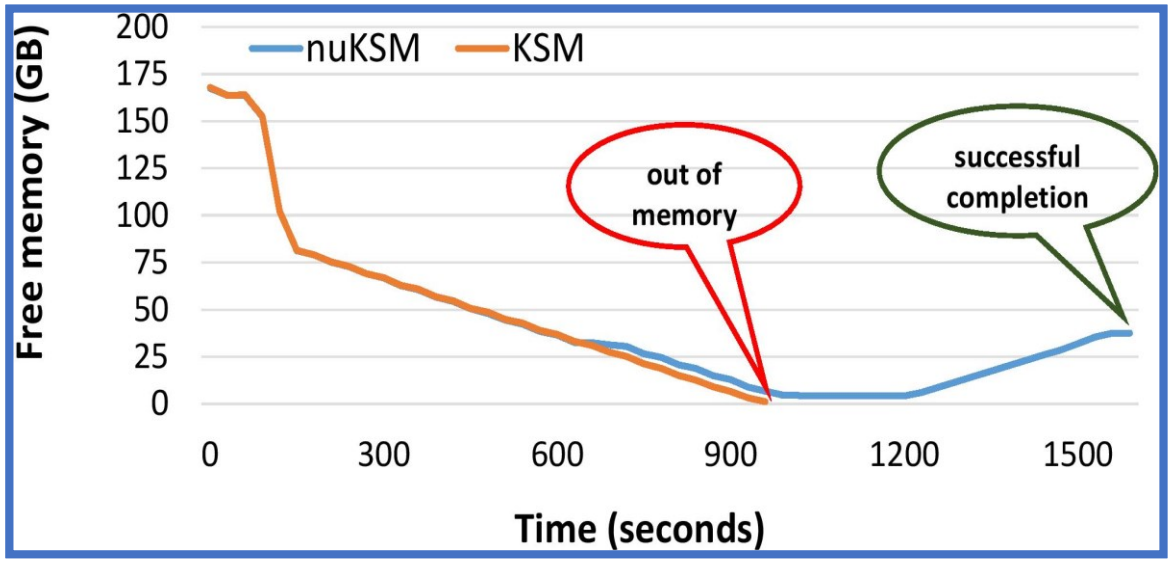
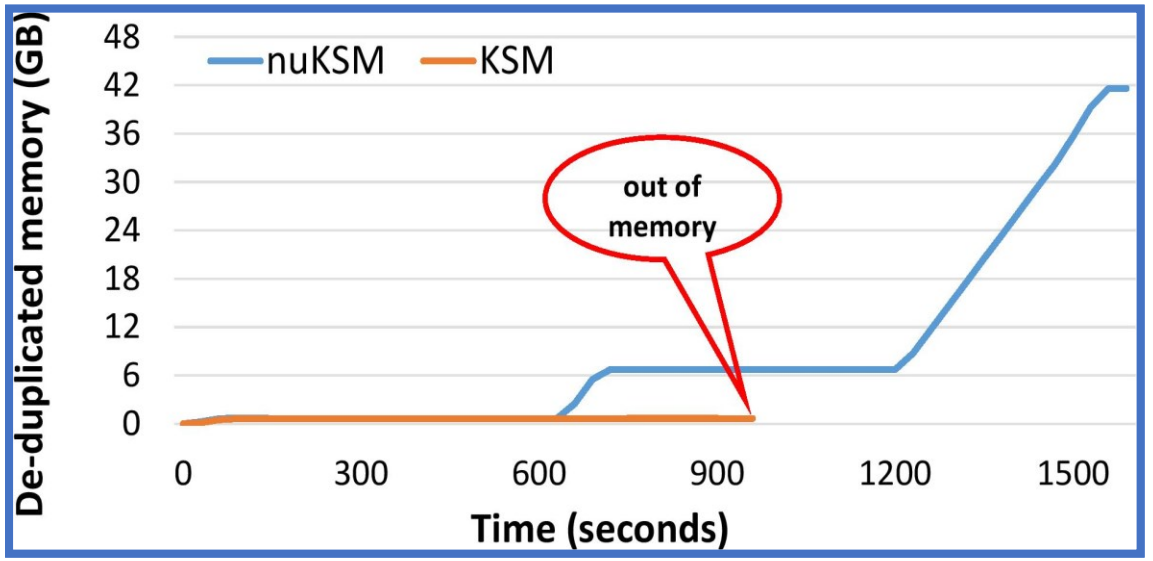


nuKSM scales better with memory size





Take-aways: NUMA-aware KSM (nuKSM)

- Observation: KSM is NUMA unaware.
  - Arbitrary (uncontrolled) performance variability
  - Subversion of priority goals
  - Low responsiveness with large memory

- Our proposal: nuKSM: NUMA-aware KSM
  - Deterministic performance and fairness
  - Inline with priority objective
  - Enhanced responsiveness

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Questions

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