Nexus: A New Approach to Replication in Distributed Shared Caches

Po-An Tsai, Nathan Beckmann, and Daniel Sanchez

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- Data replication reduces the access latency of non-uniform caches (NUCA)
  - But replicating too aggressively leads to more cache misses
- Prior adaptive techniques focus on **which data to replicate at each core**
  - Data that is not replicated locally still incurs high latency
- Nexus instead focuses on **how much to replicate across the system**
  - Chooses the best number of replicas for the whole read-only working set
  - Lets cores access replicas beyond their local bank
  - Outperforms a state-of-the-art replication technique **by up to 90%**

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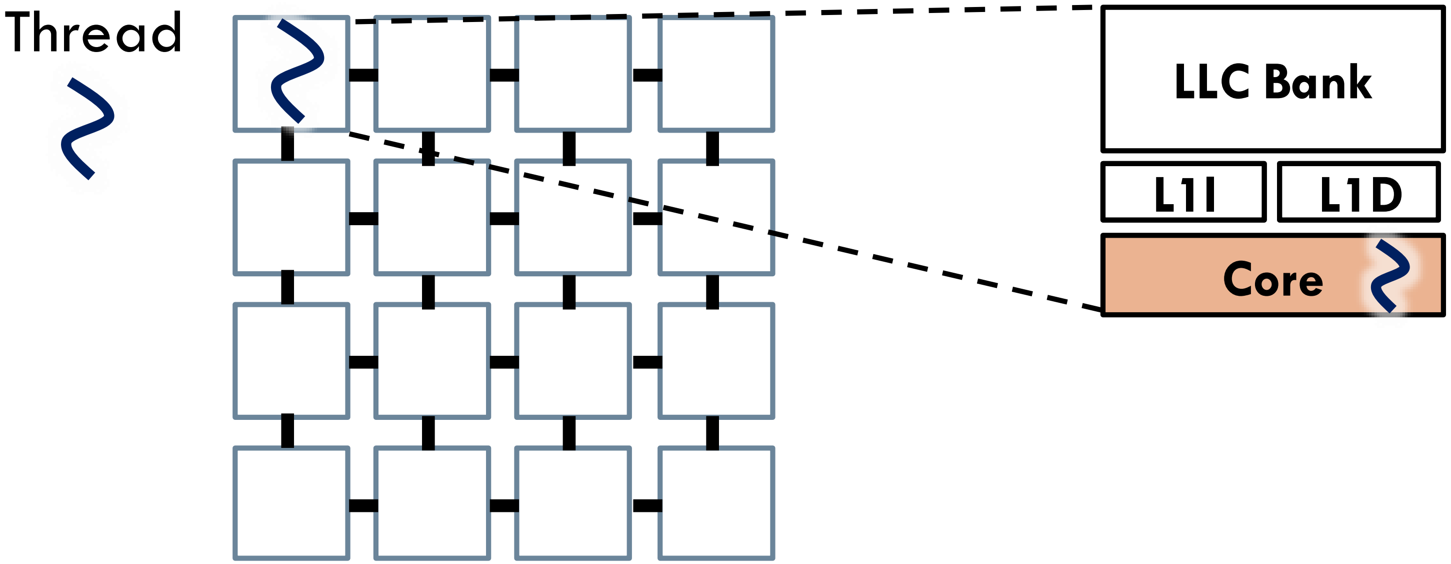

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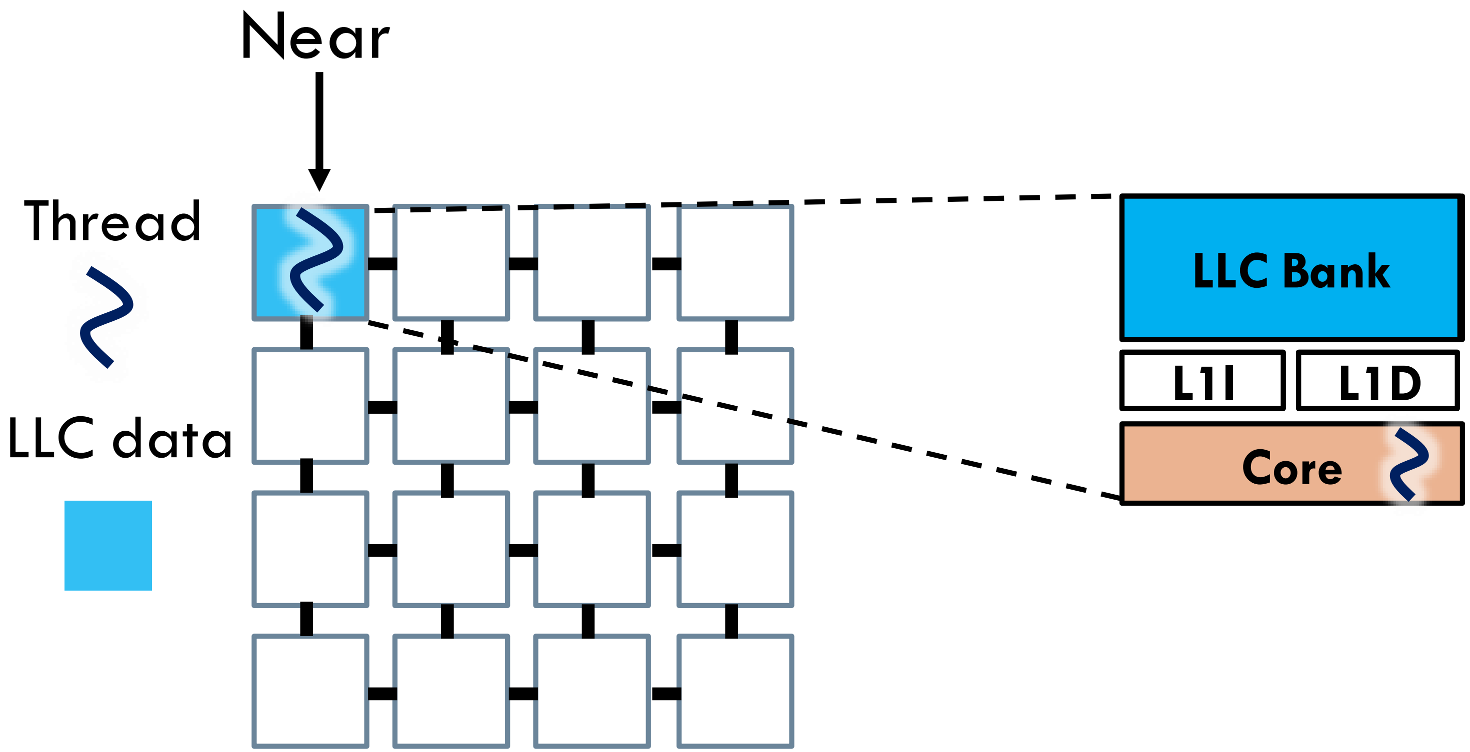

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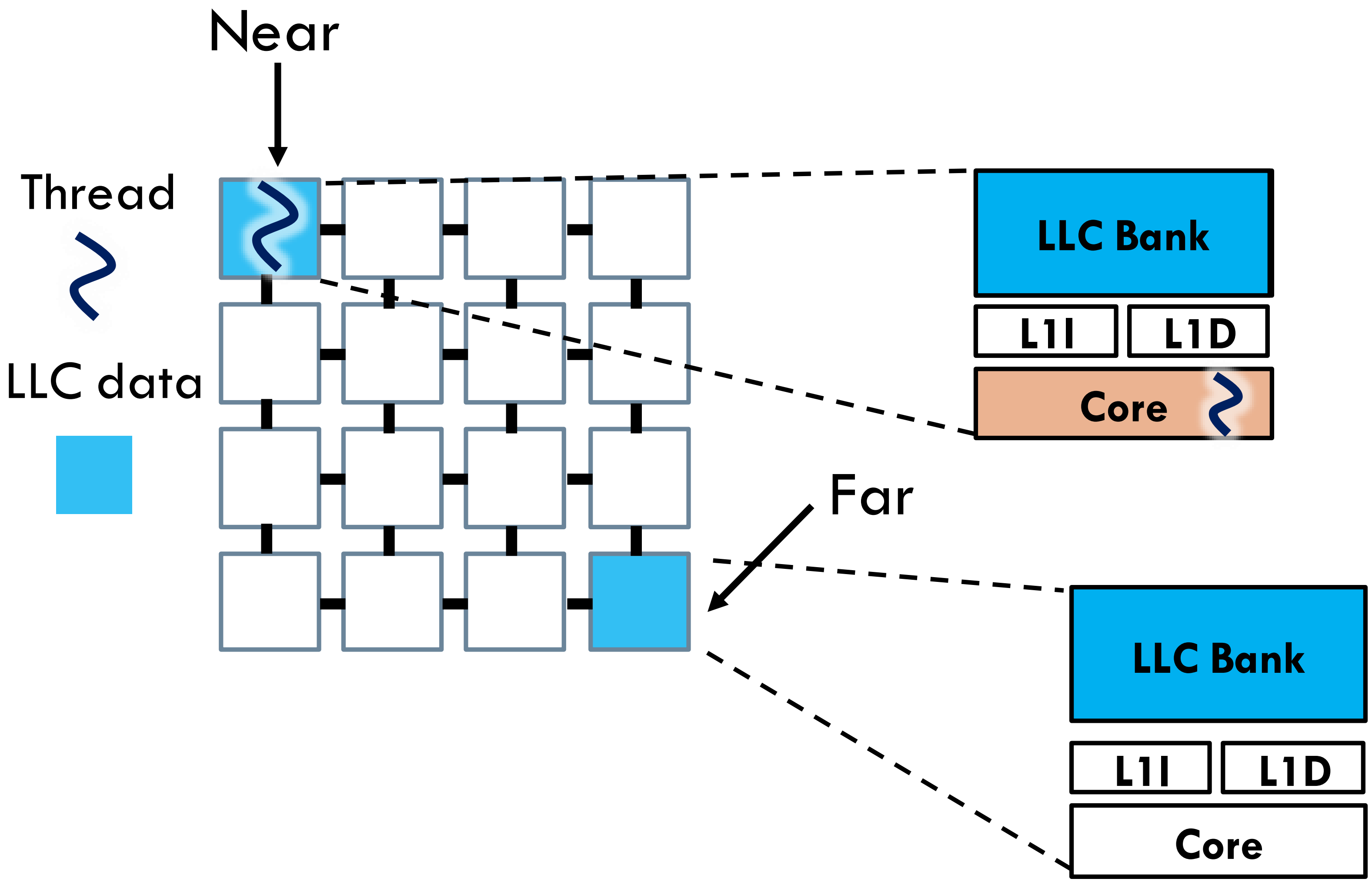

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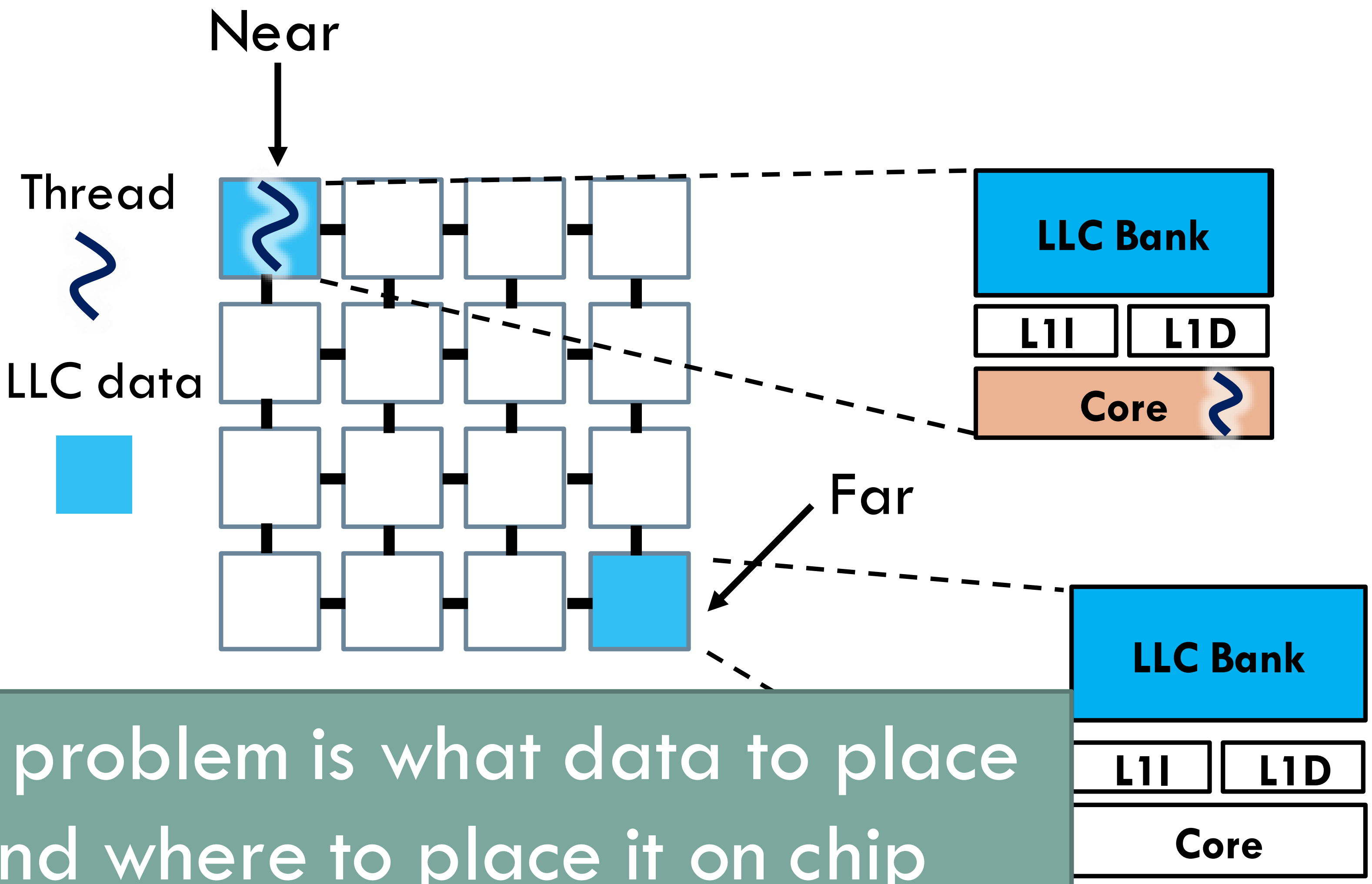
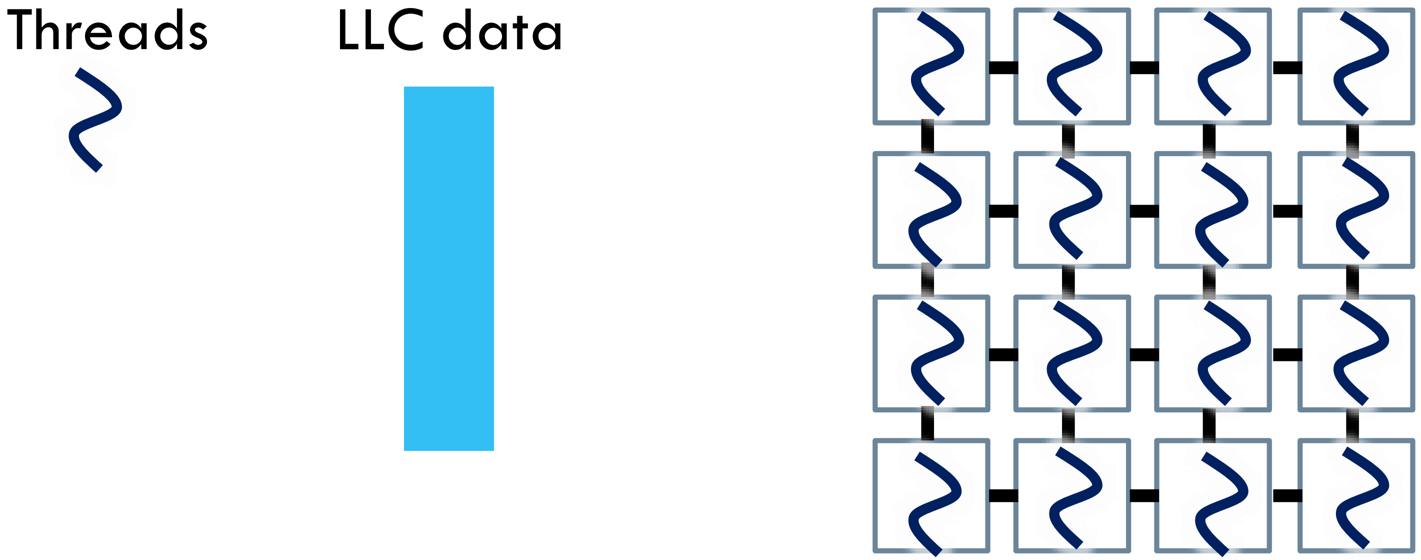


Key problem is what data to place and where to place it on chip

Static NUCA (S-NUCA) spreads data using a fixed line-to-bank mapping



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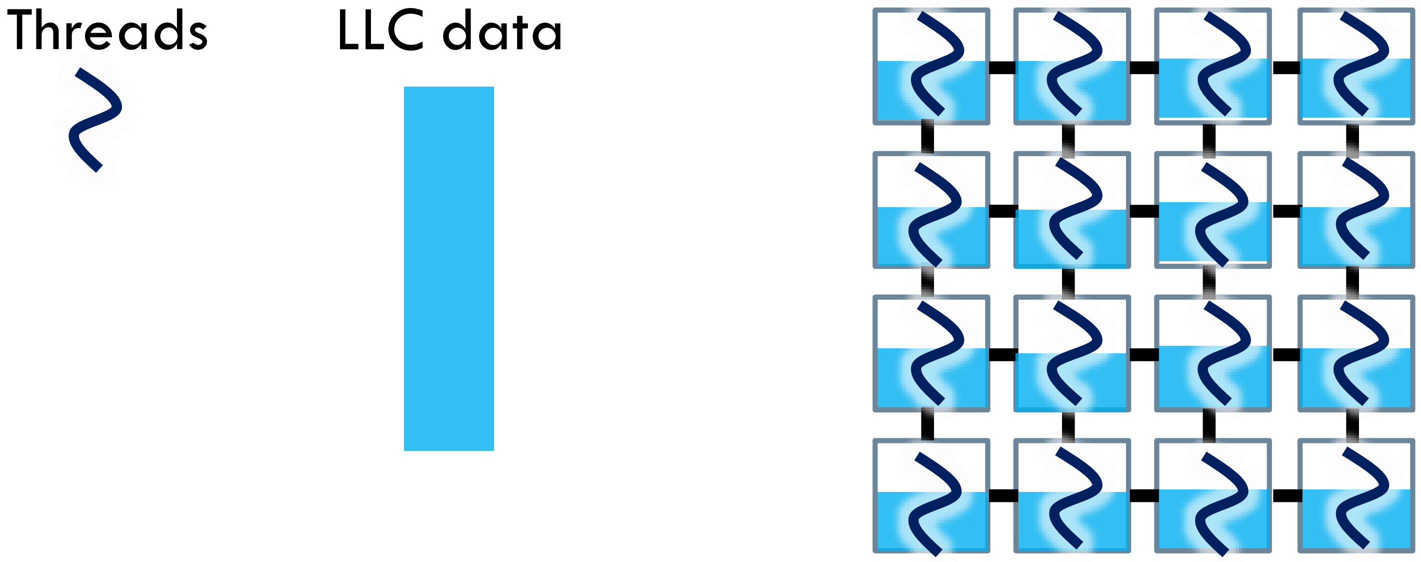

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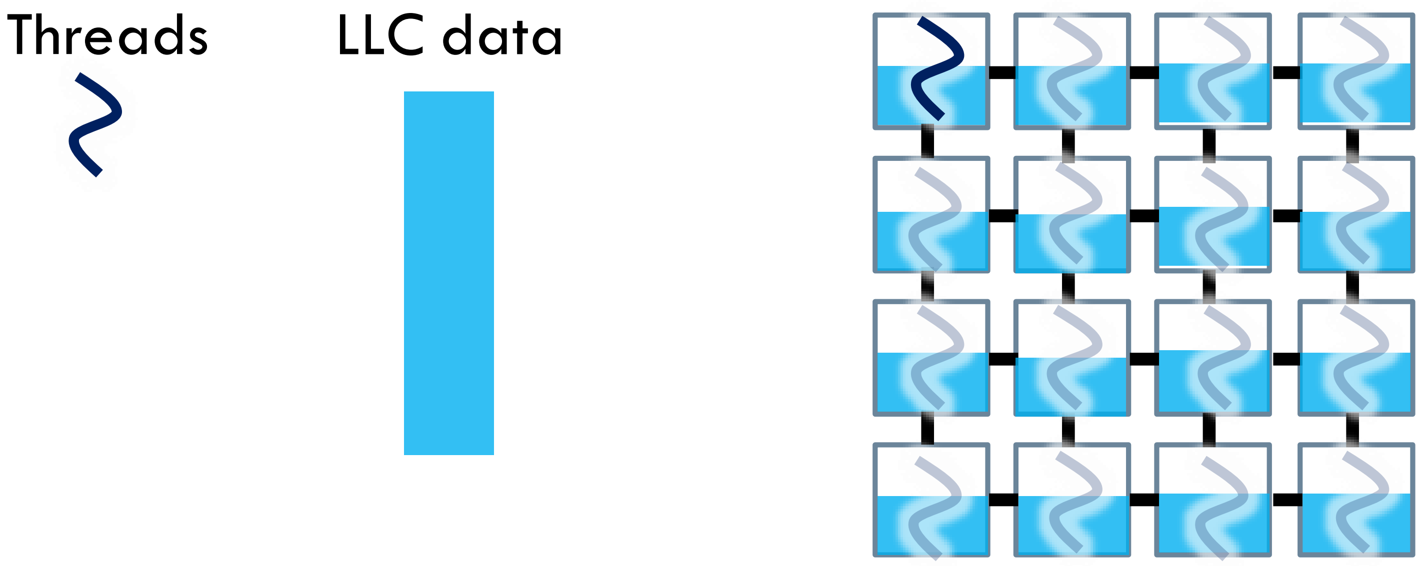

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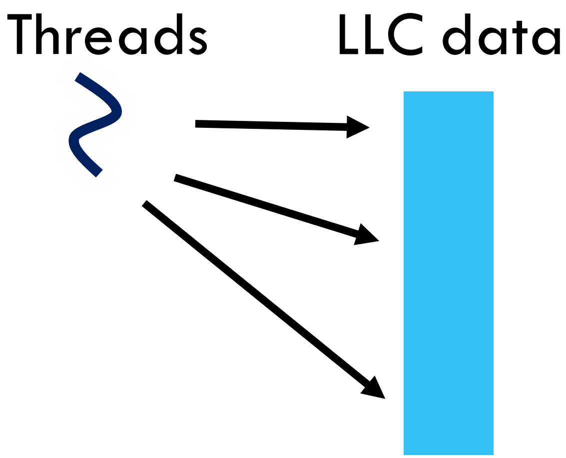
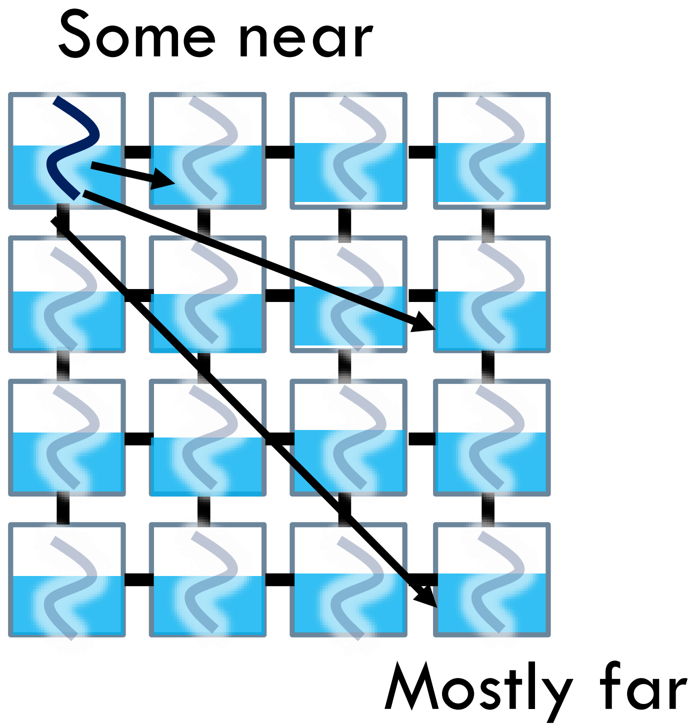
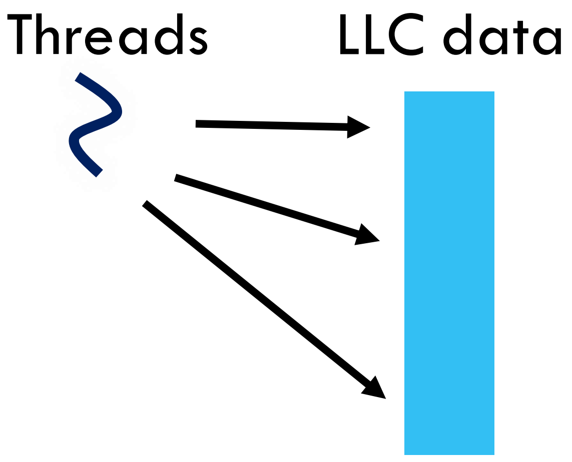
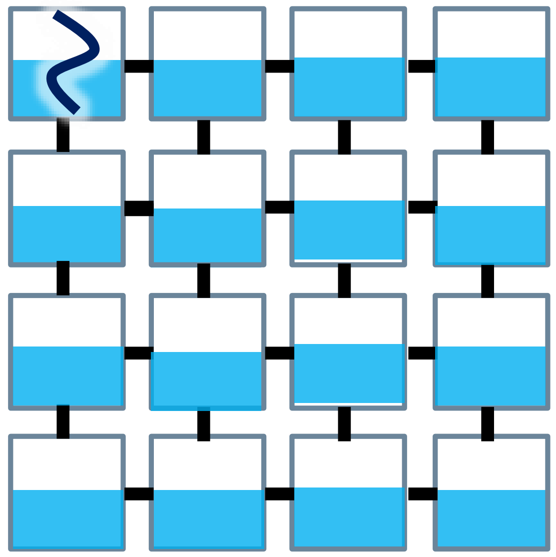




Simple but large average distance

Replication reduces the distance to read-only data





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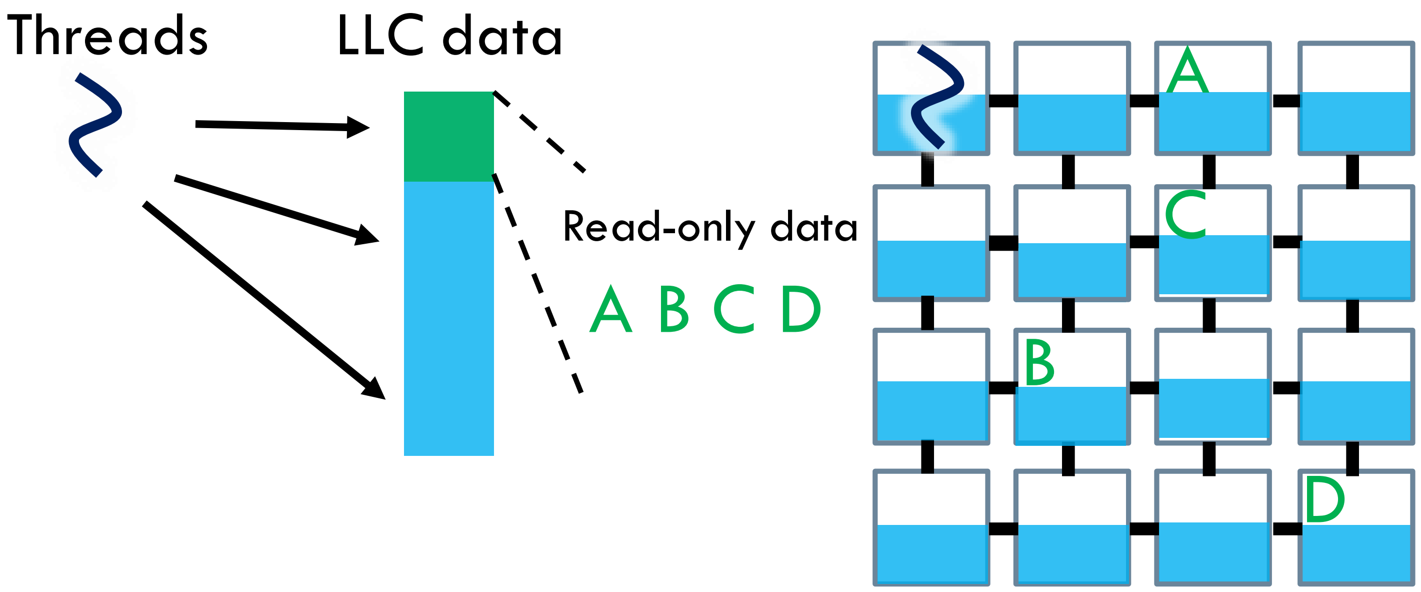

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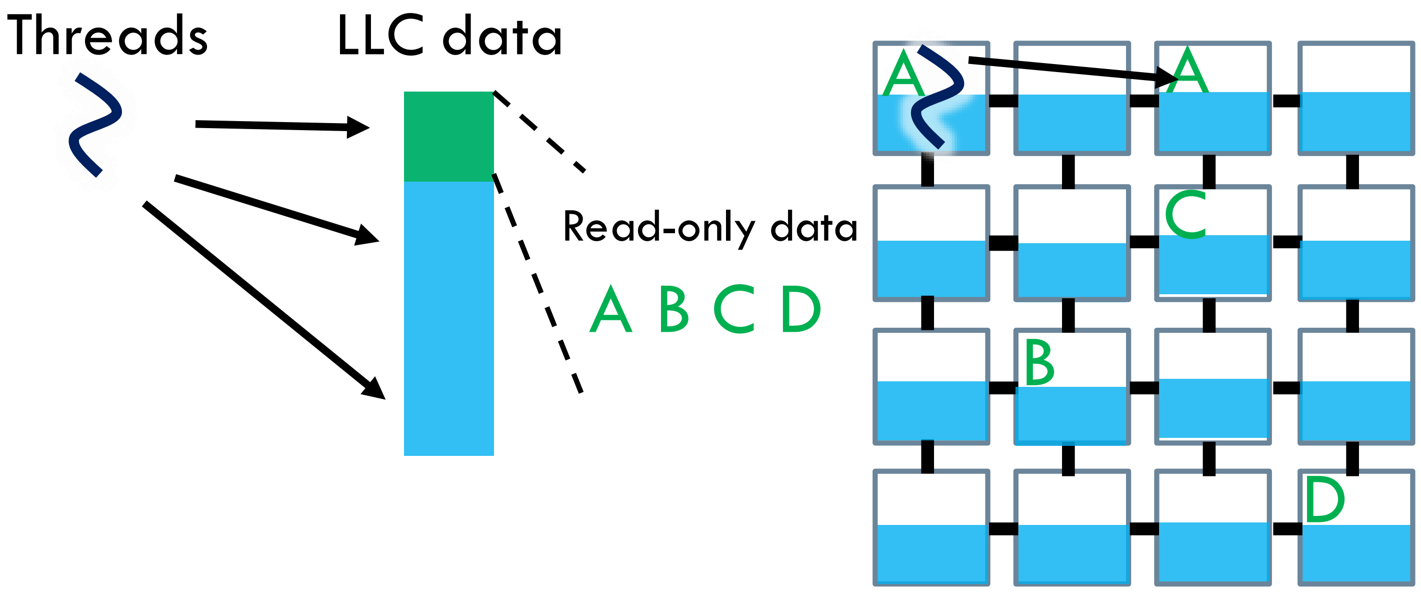

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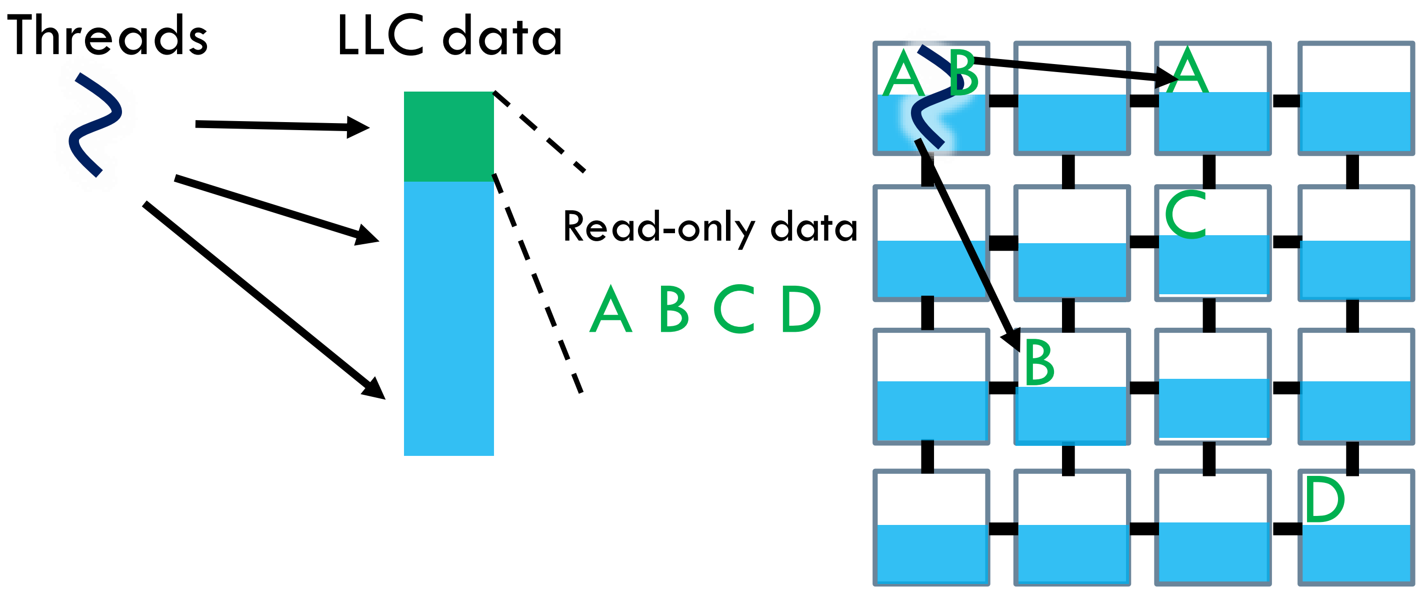

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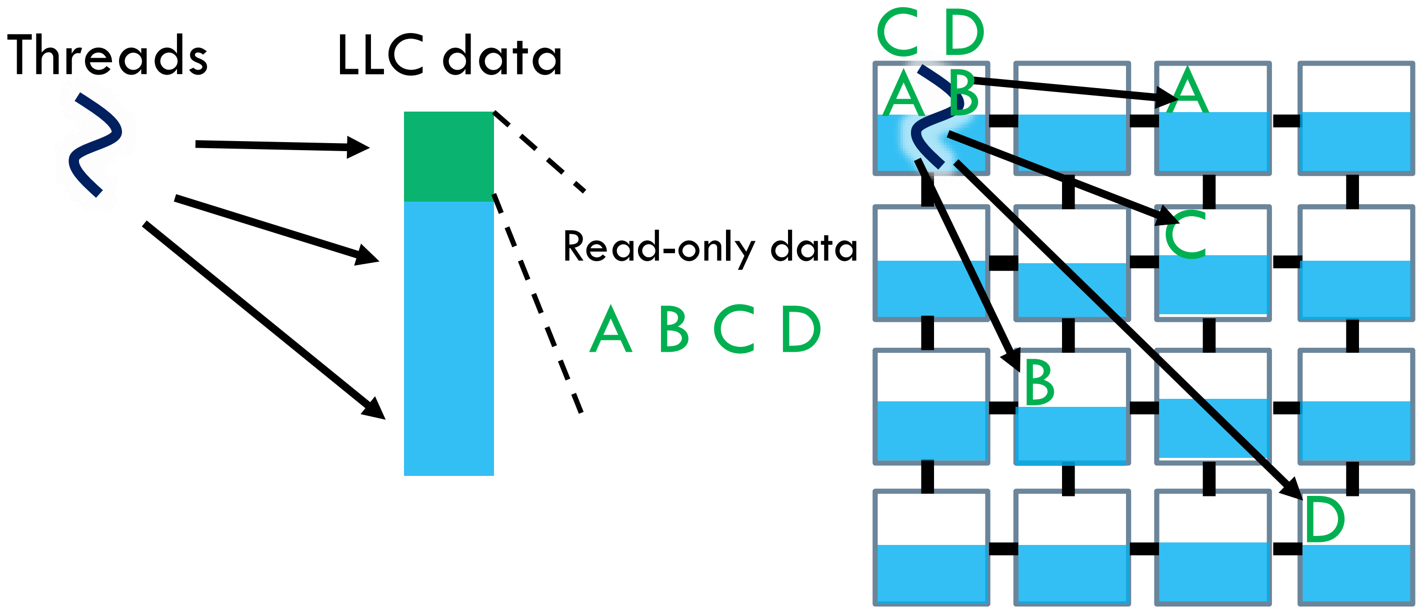

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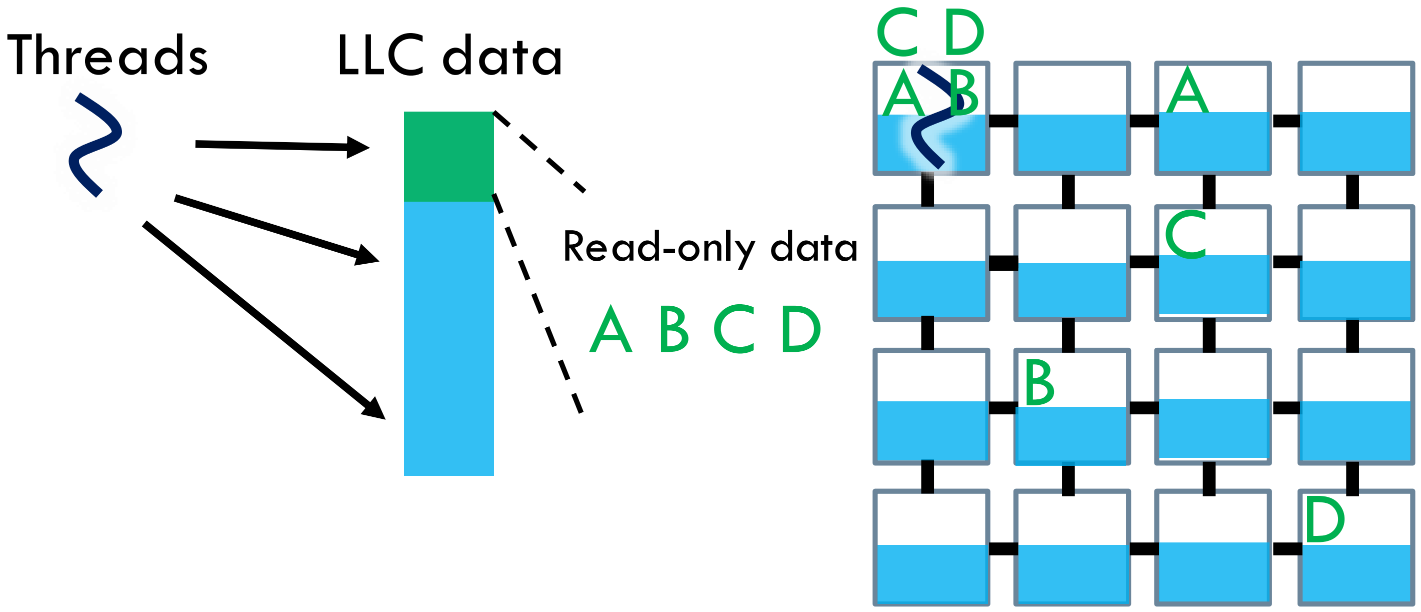
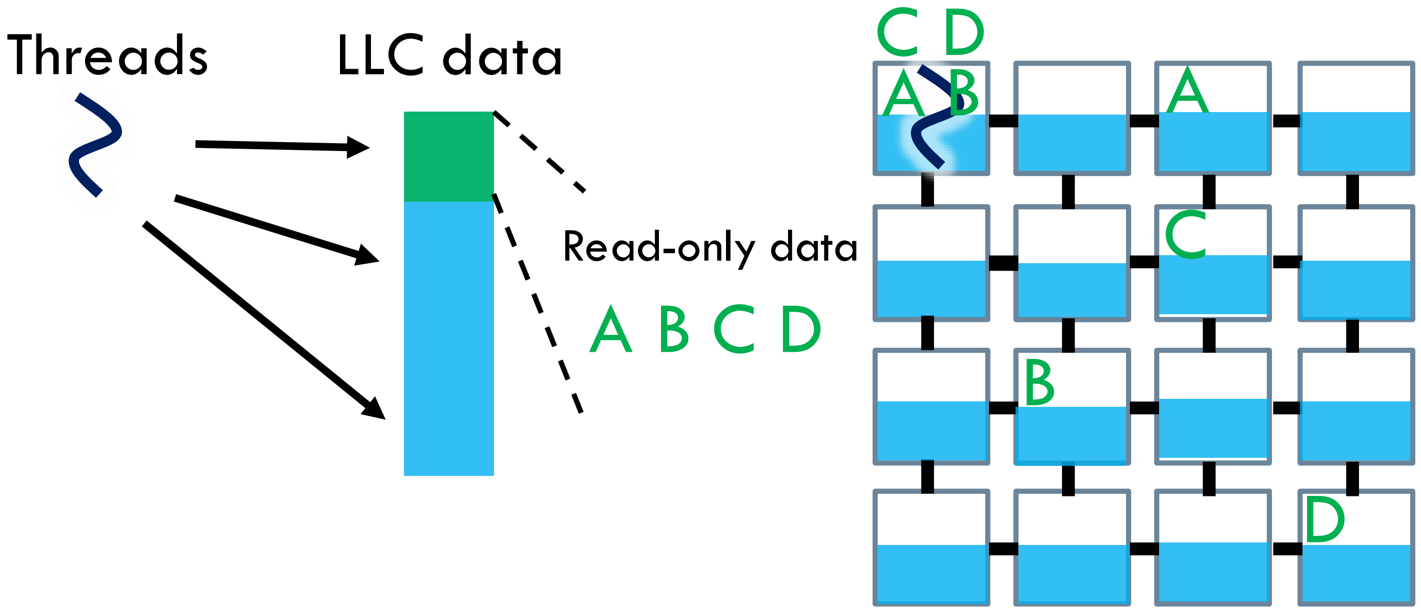


Replication reduces the distance to read-only data

Cache replicated read-only lines locally and check the local bank first.

Upon a miss in the local bank, check the directory (at line's original location).



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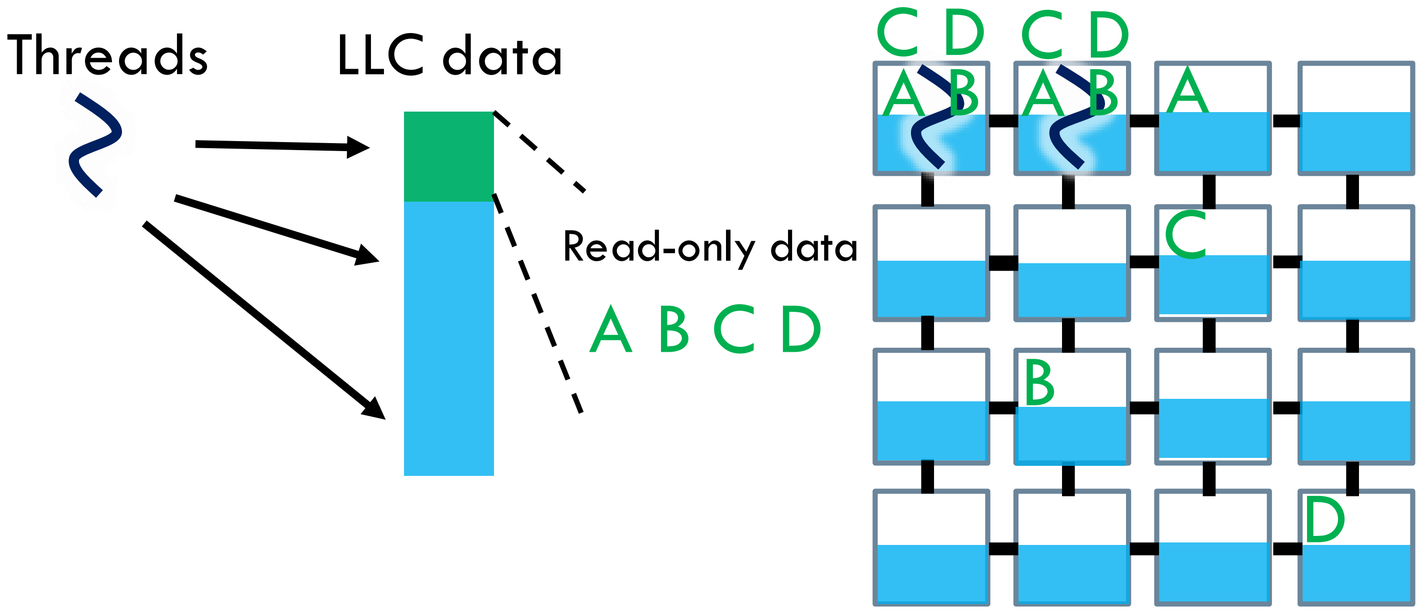

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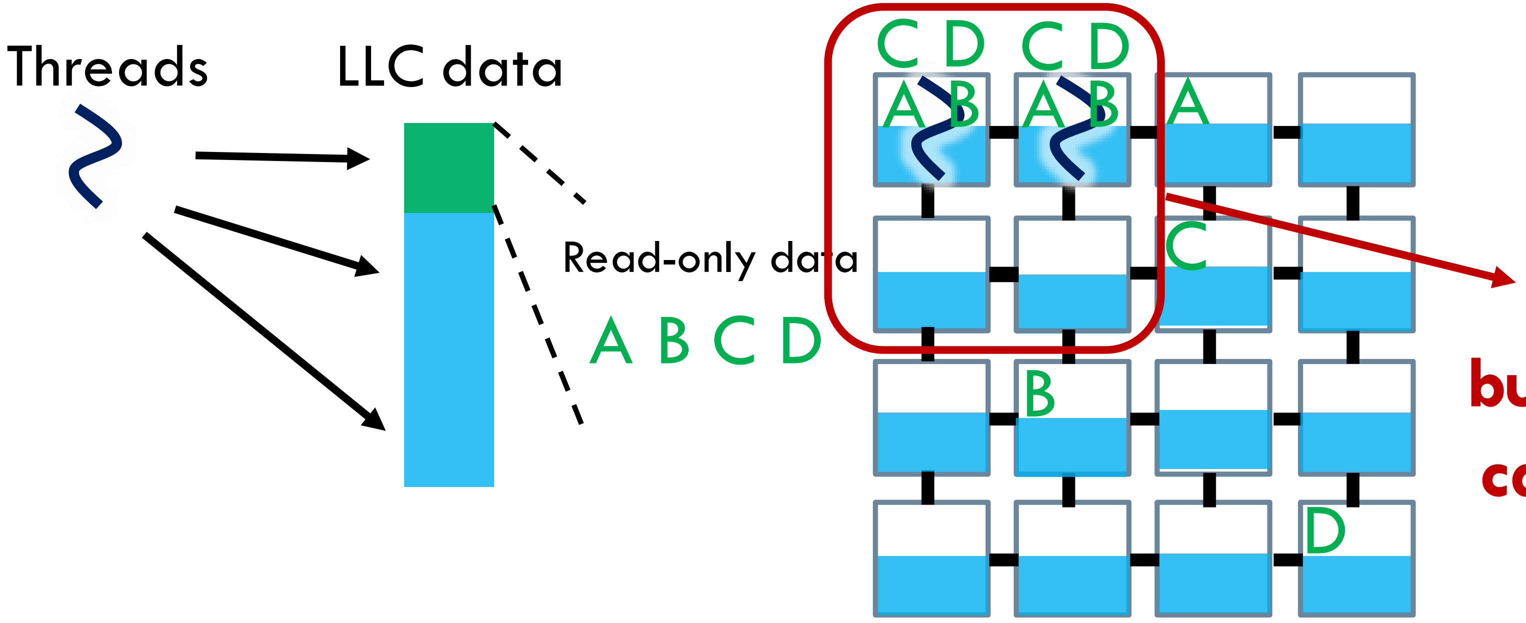

A, B, C, D are local, but replicated lines compete for cache capacity with other data

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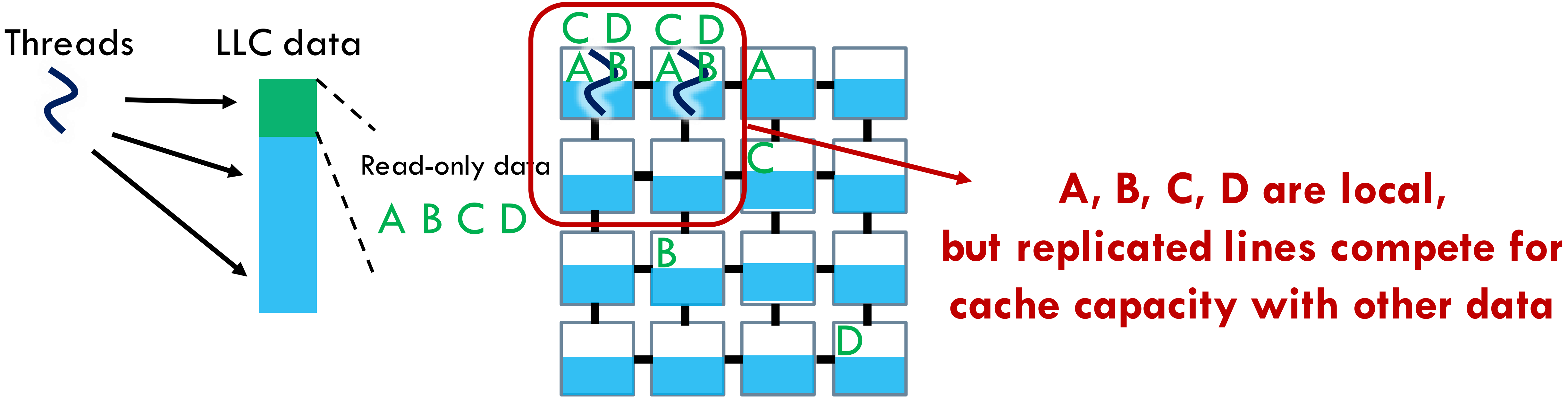
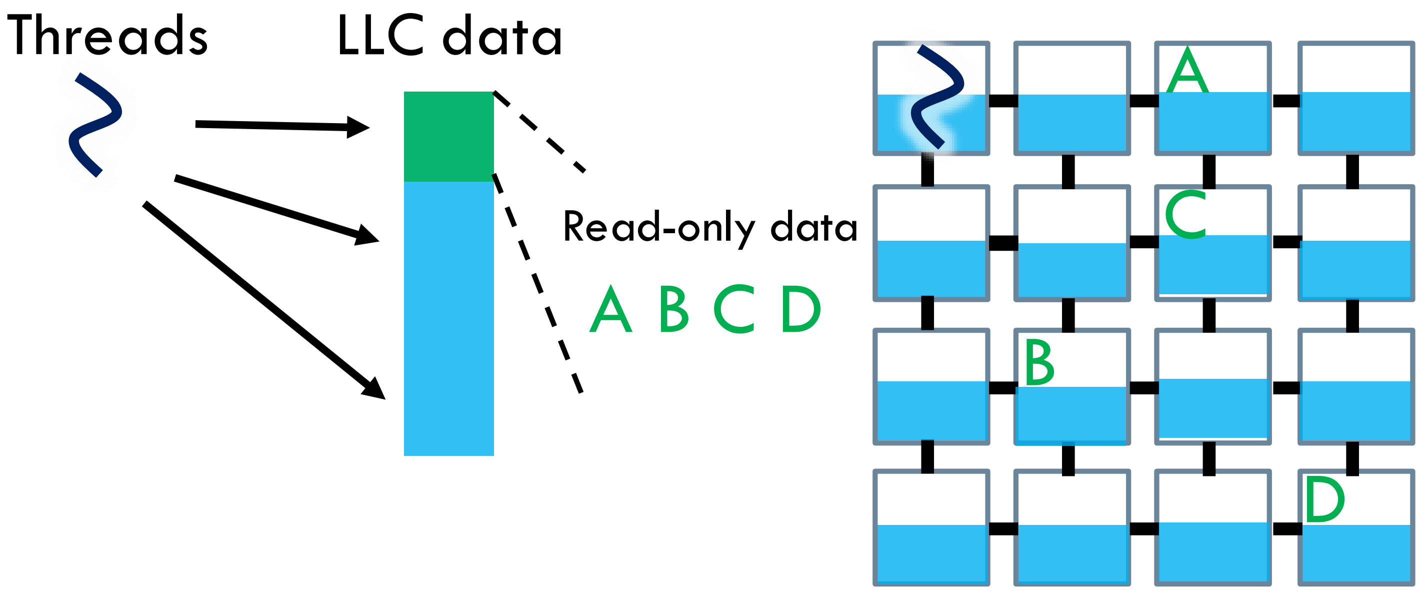


Replicating too aggressively causes more cache misses than no replication

Adaptive replication in directory-based dynamic NUCAs



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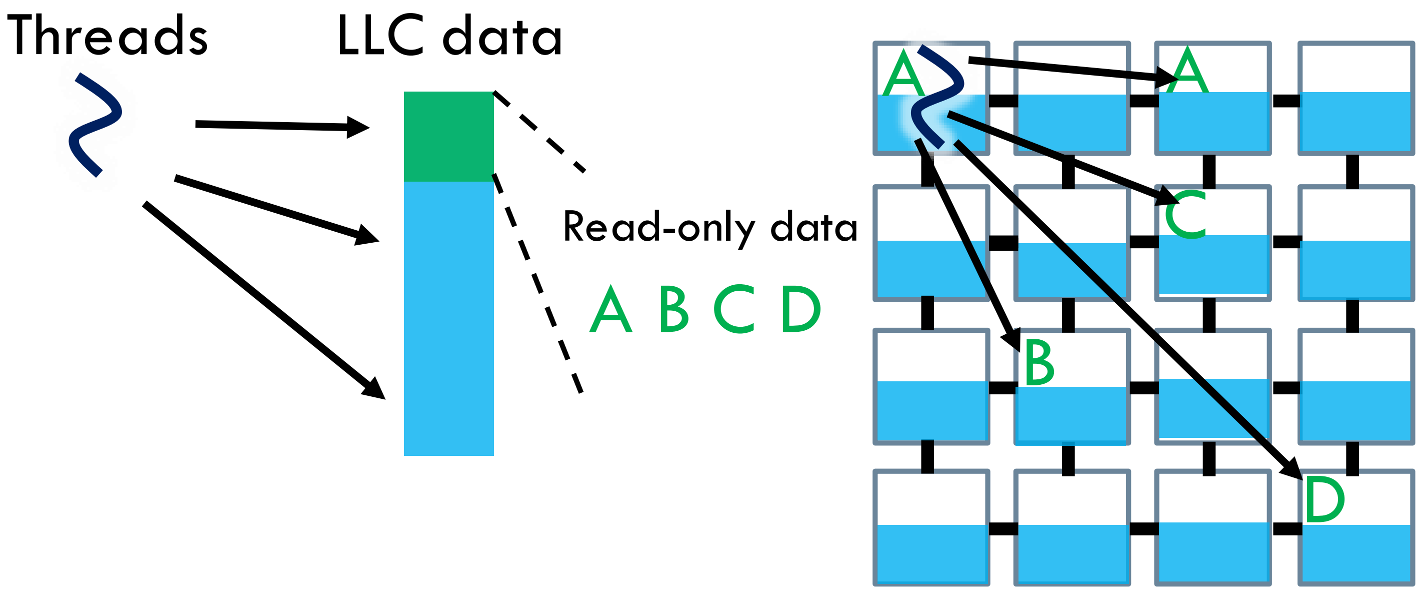

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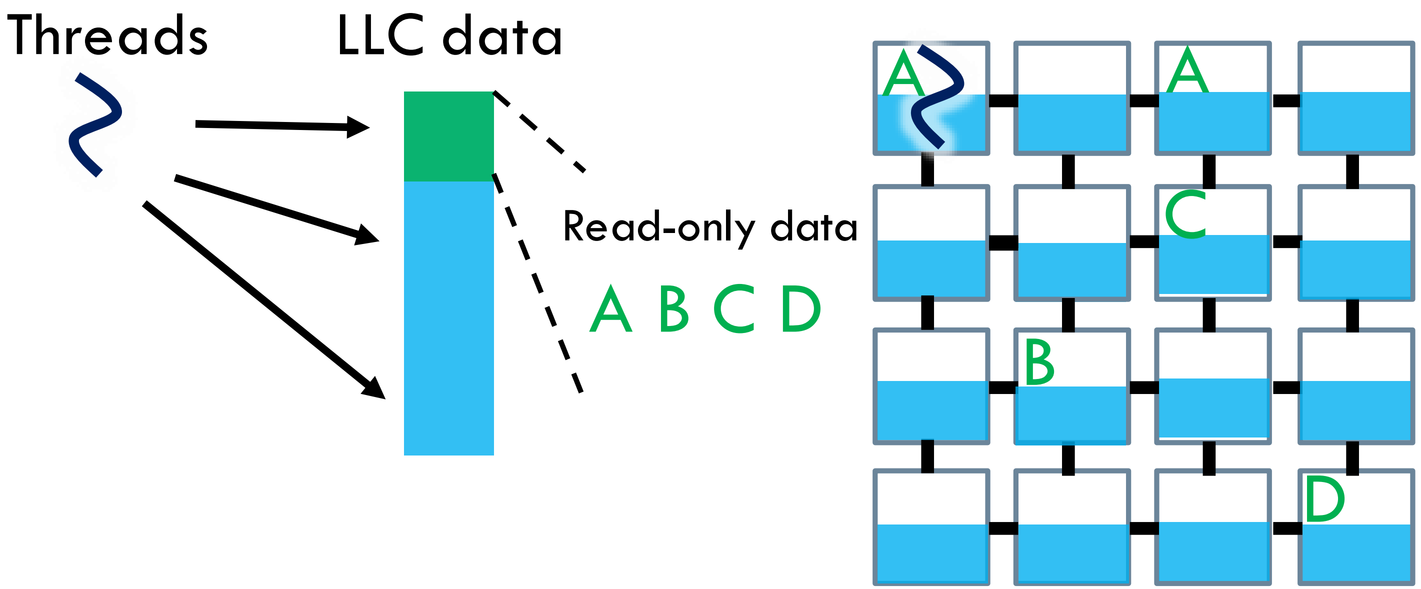

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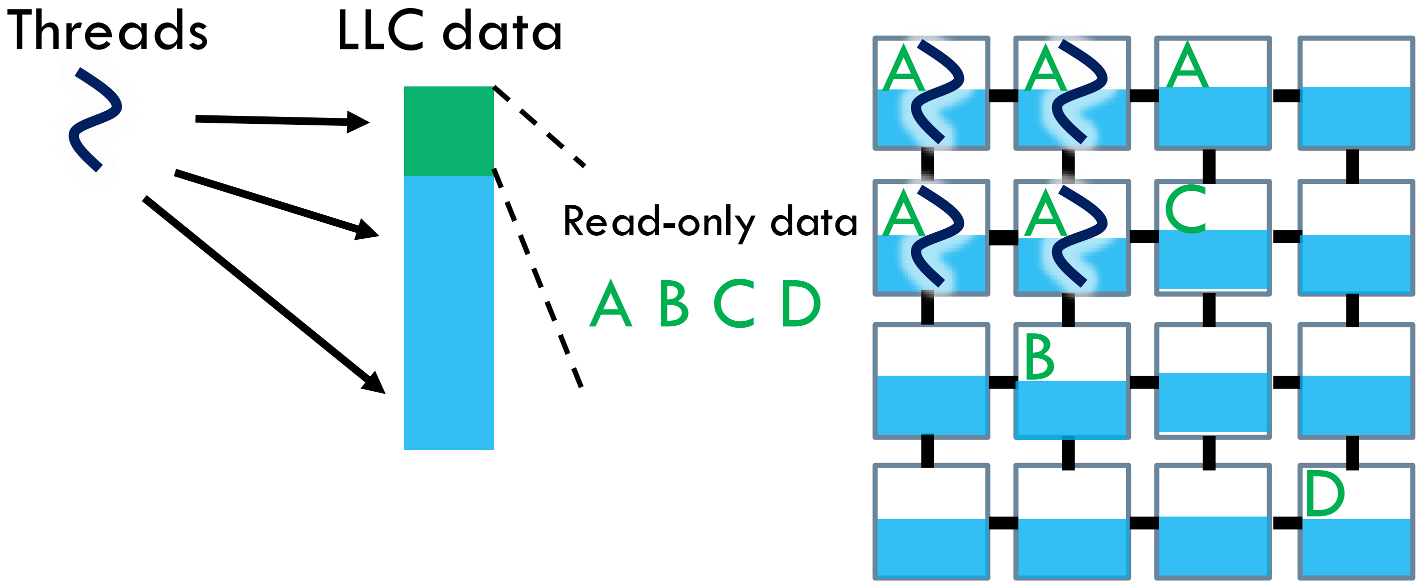

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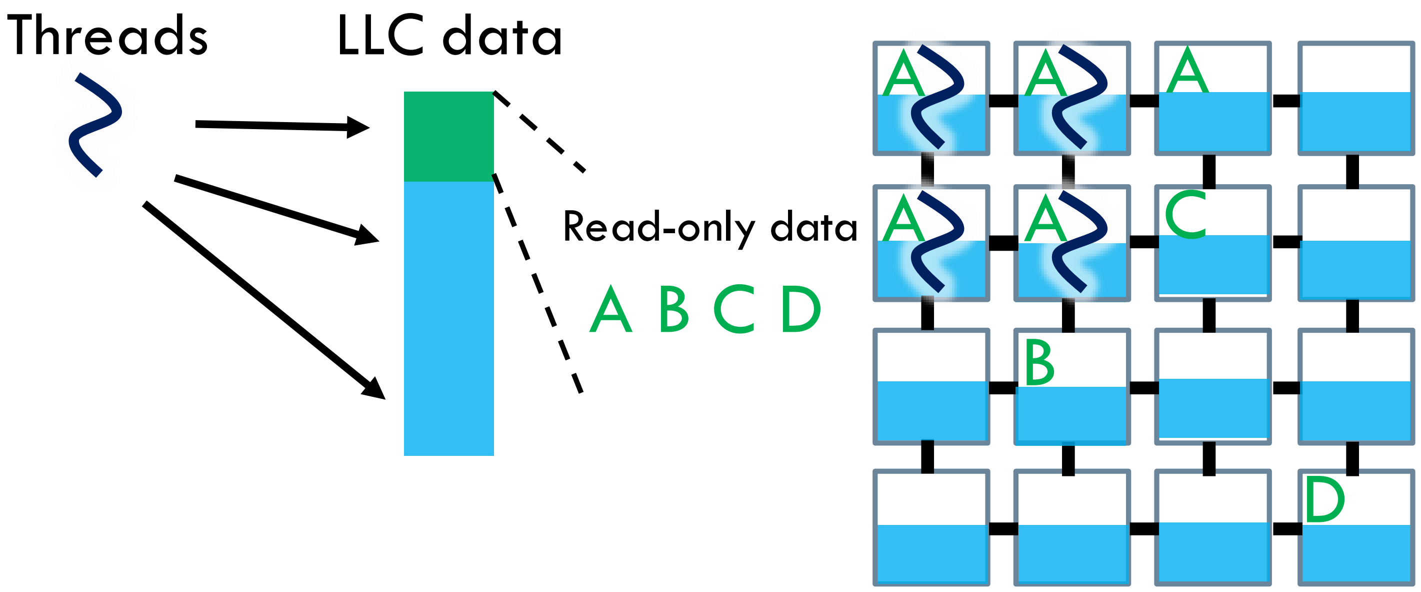

A is nearby,
but B, C, D are still far away

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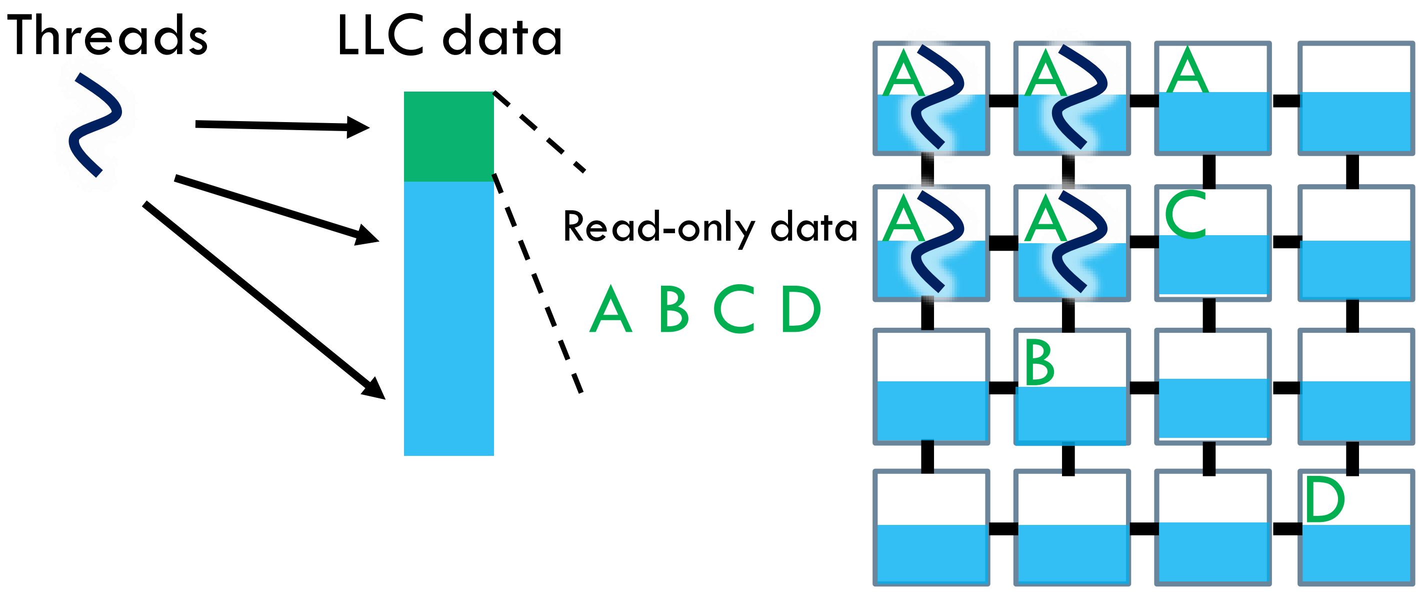

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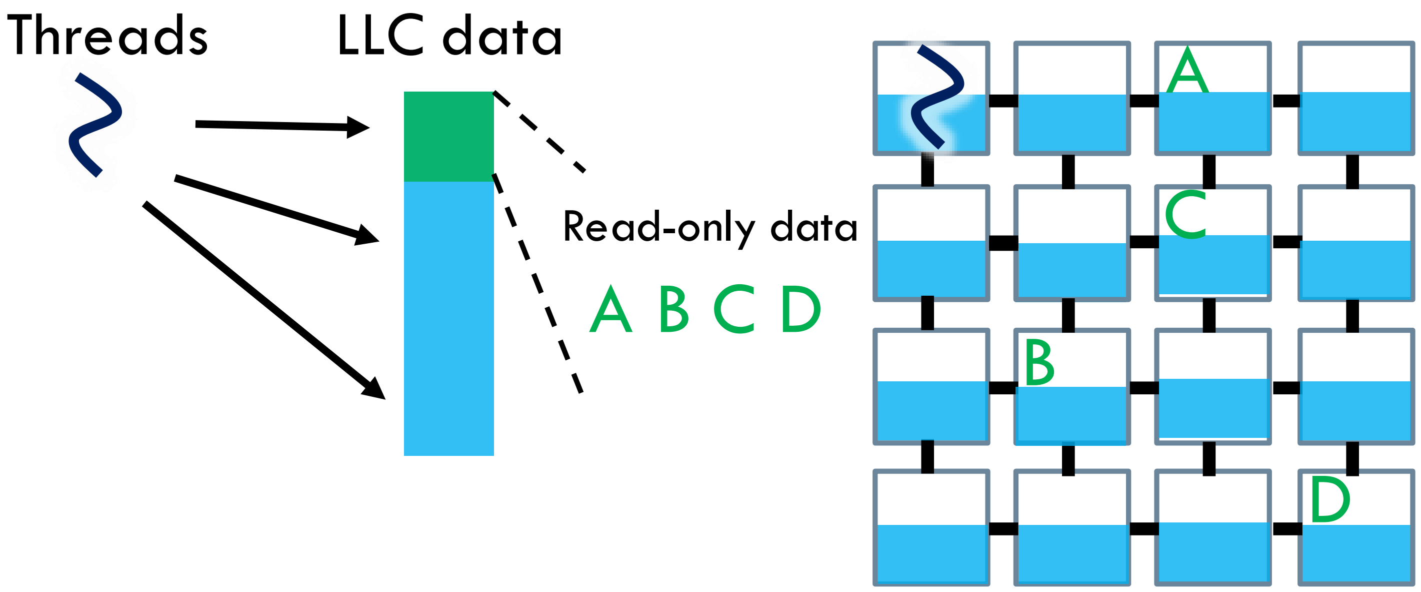

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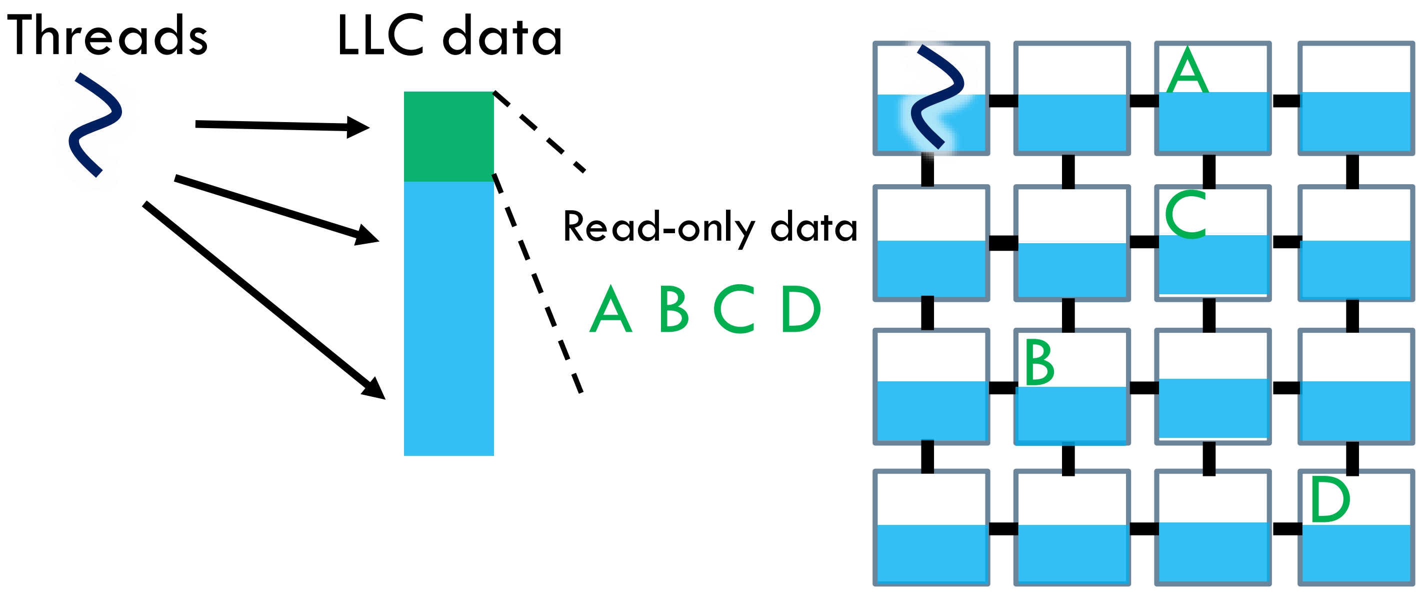

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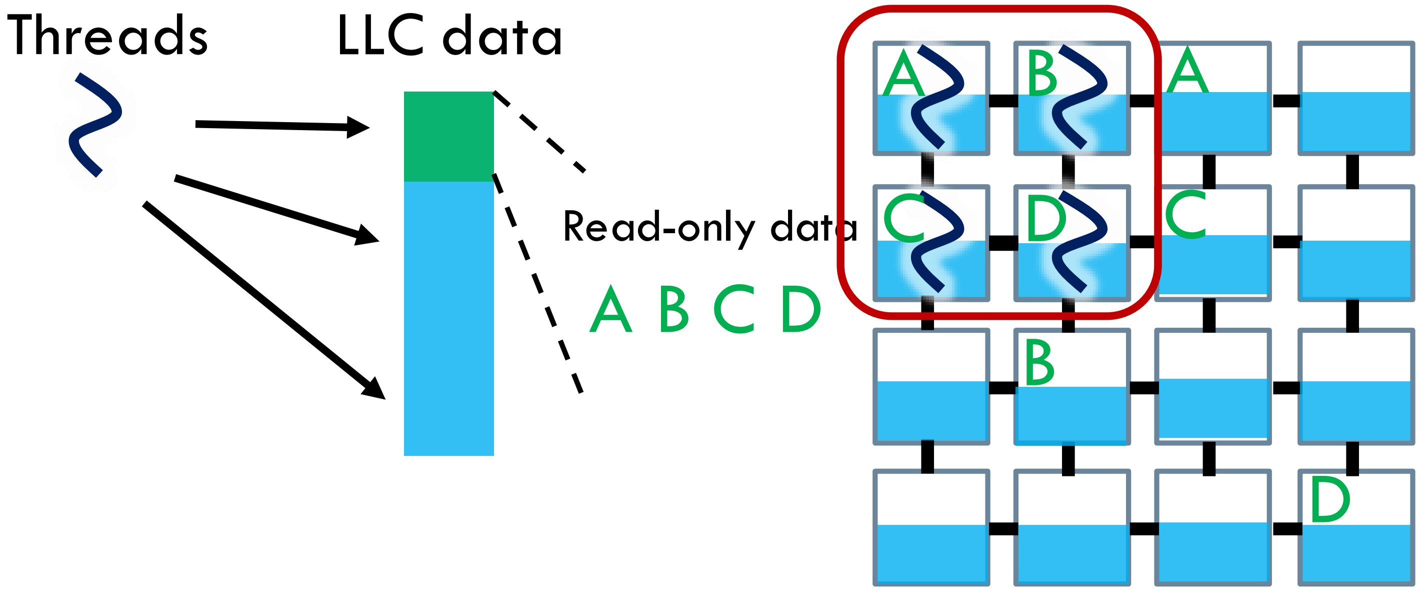

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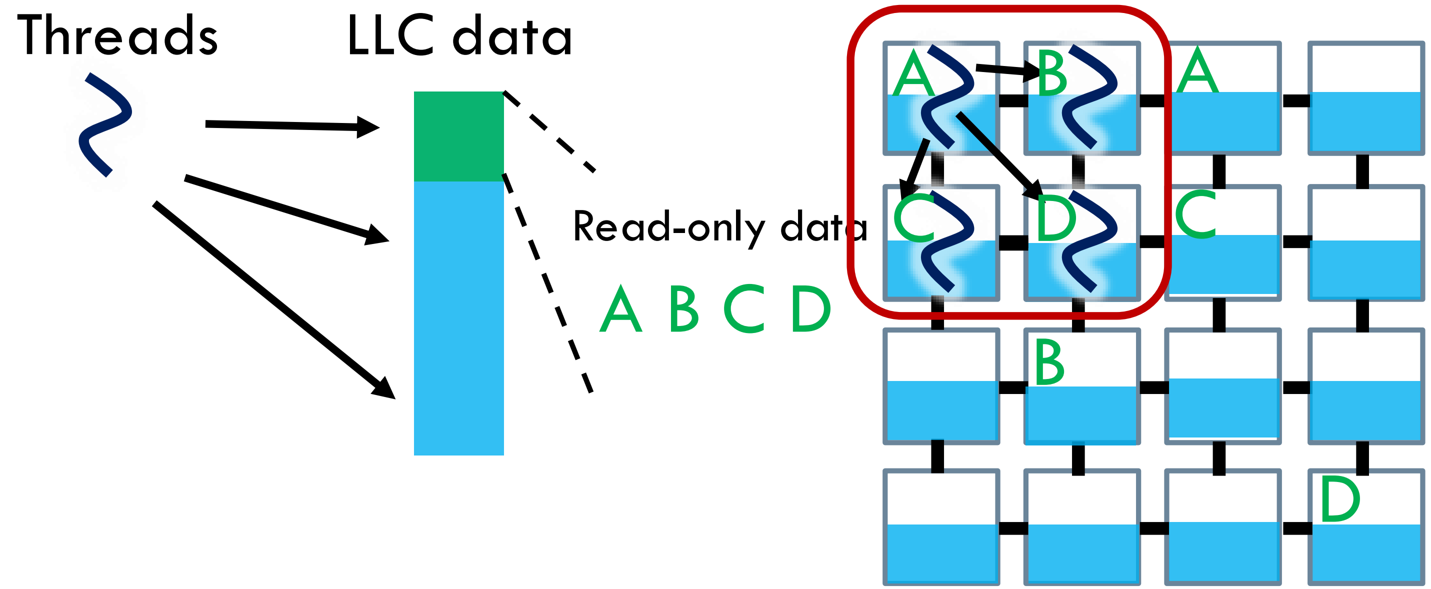

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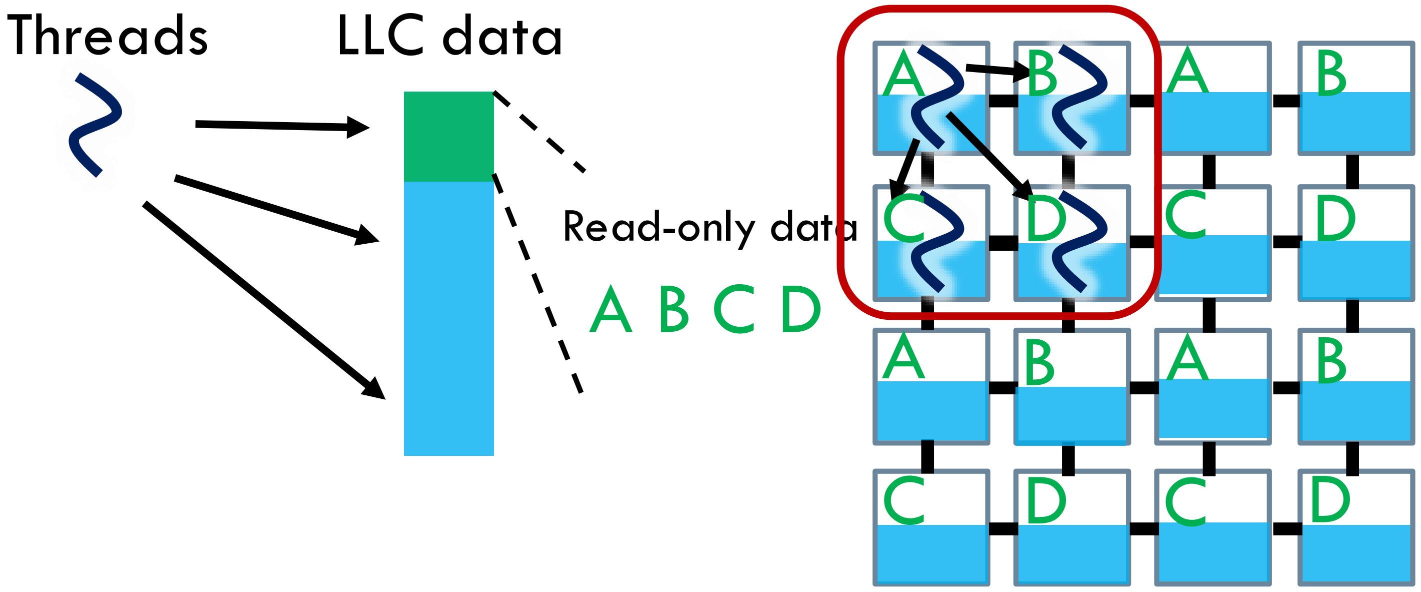

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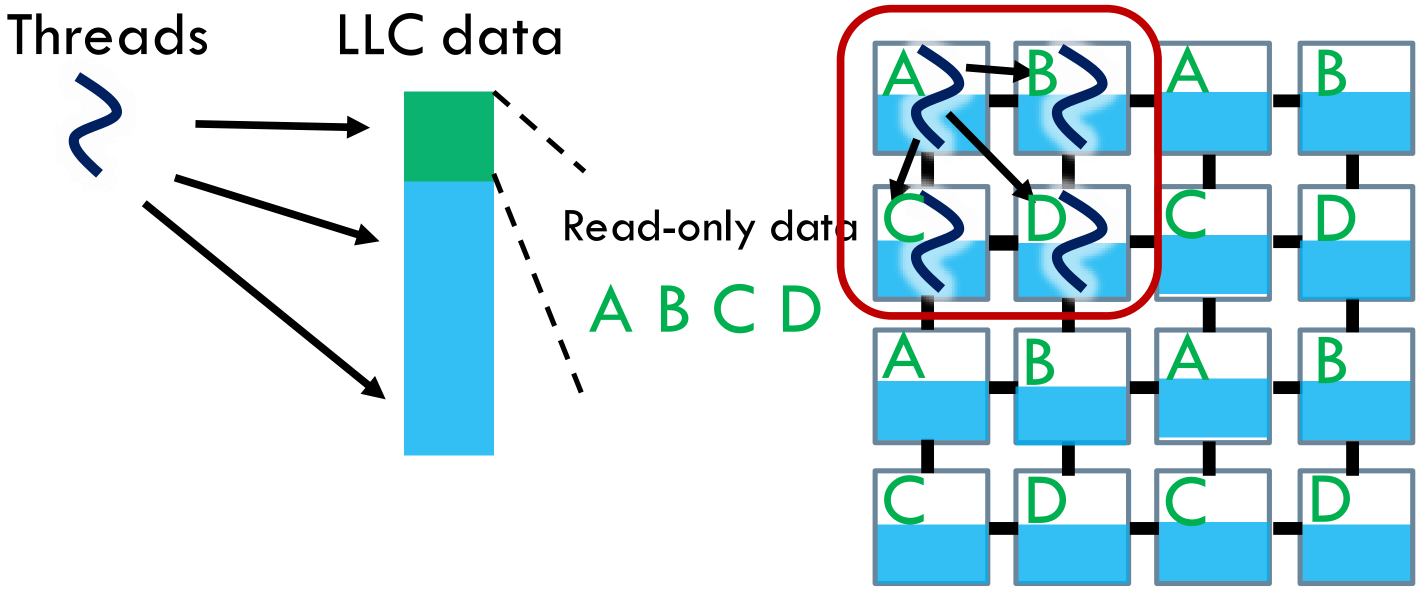

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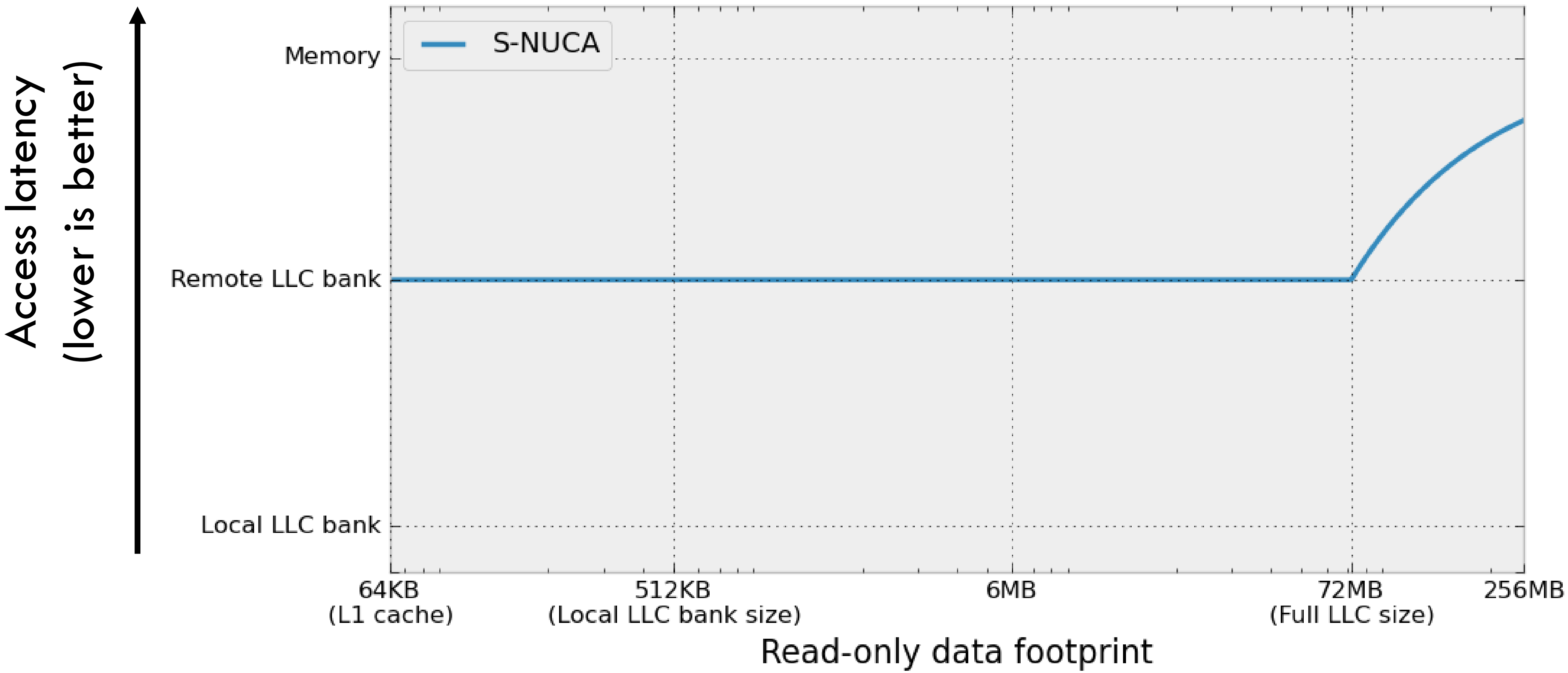
All threads enjoy fast access to all read-only data by replicating beyond their local bank

An experiment to show why and when Nexus is better

A multithreaded workload that regularly scans over shared read-only data



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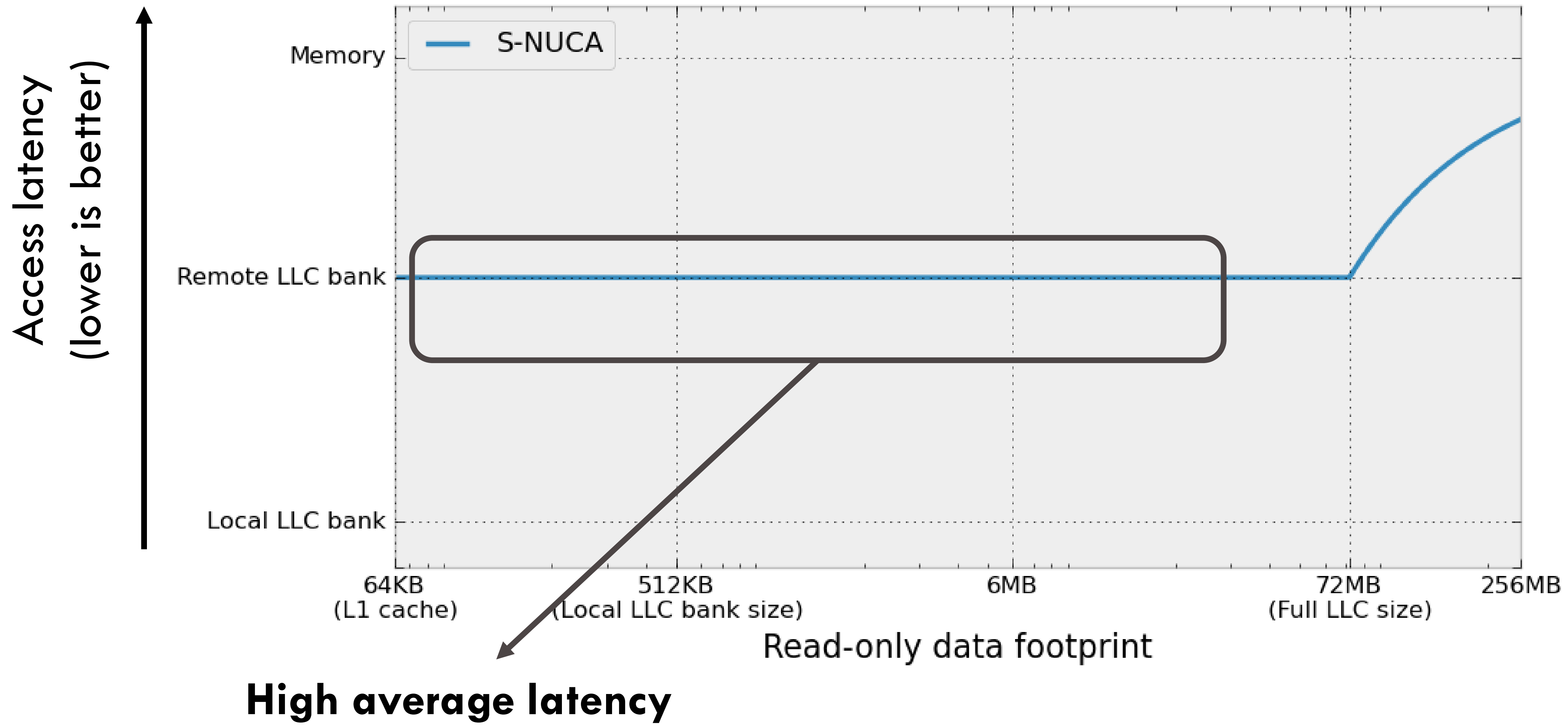

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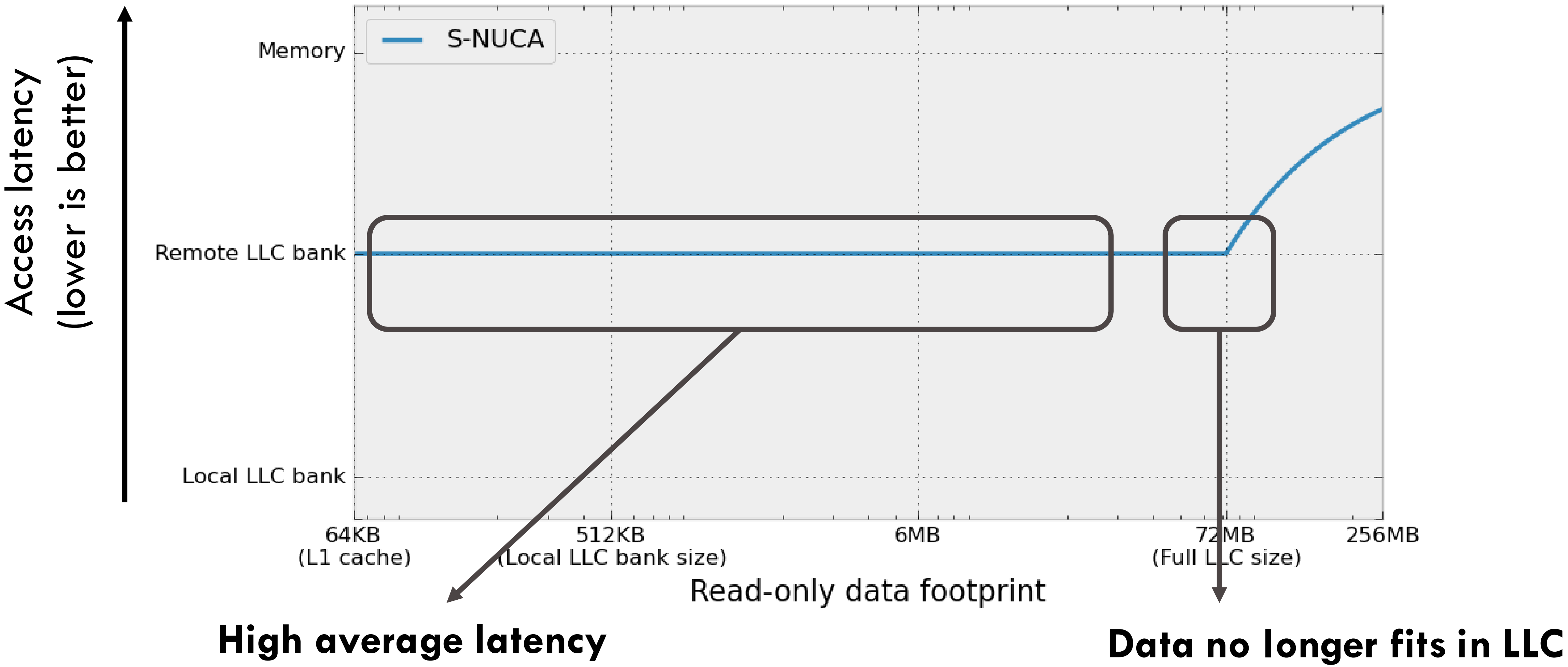

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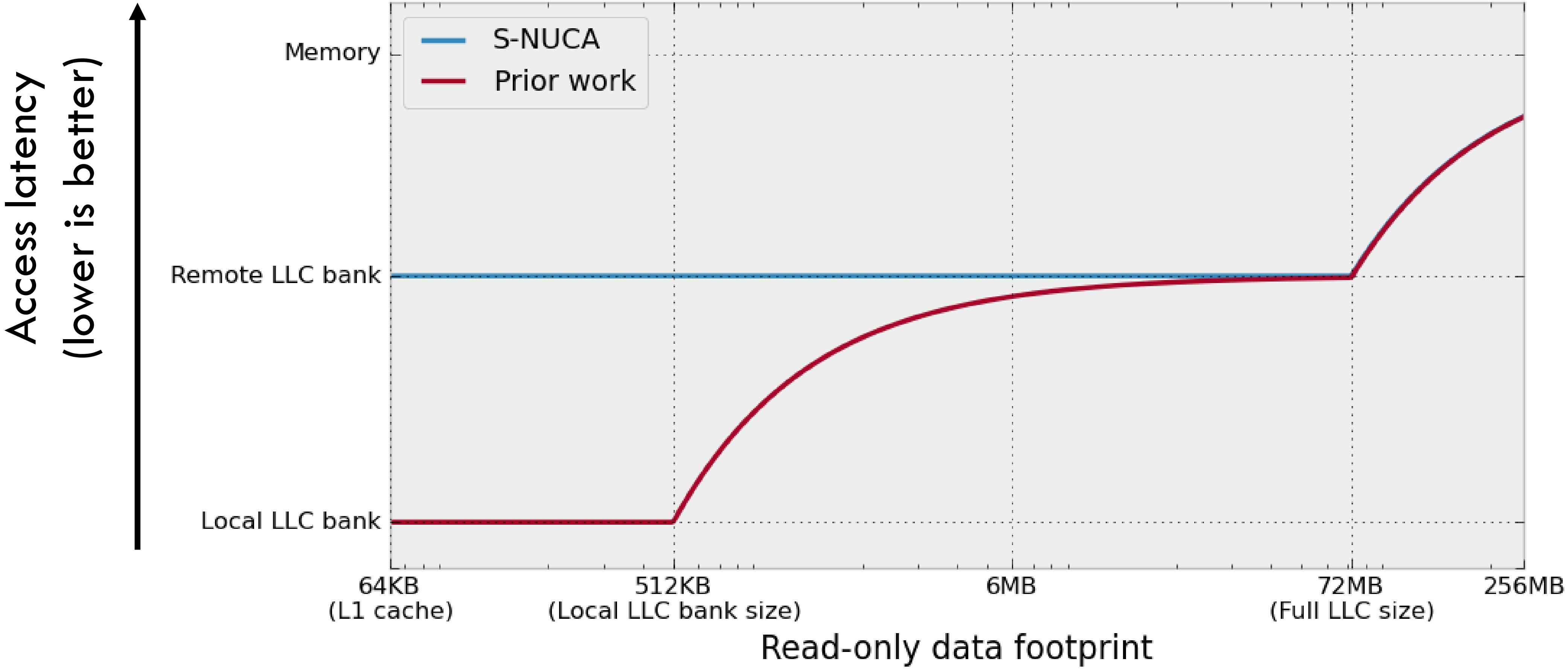

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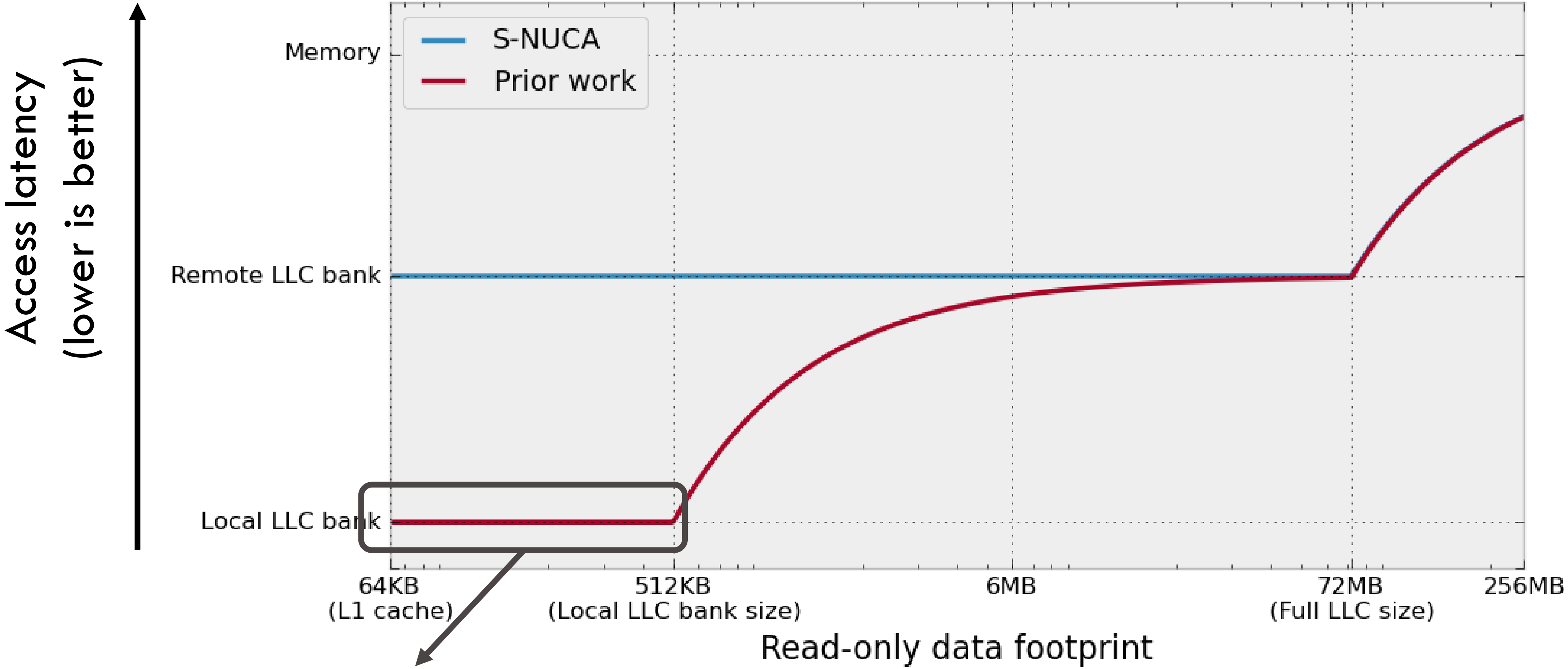

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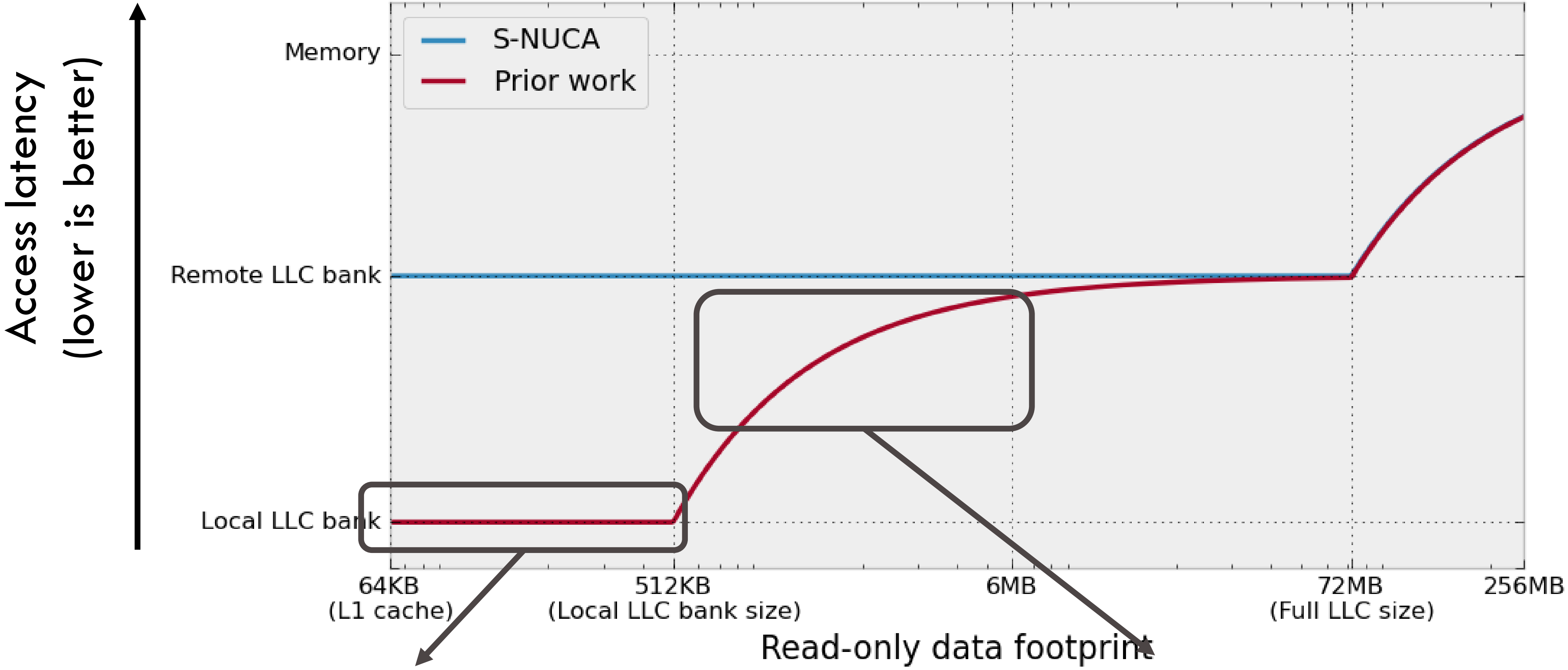
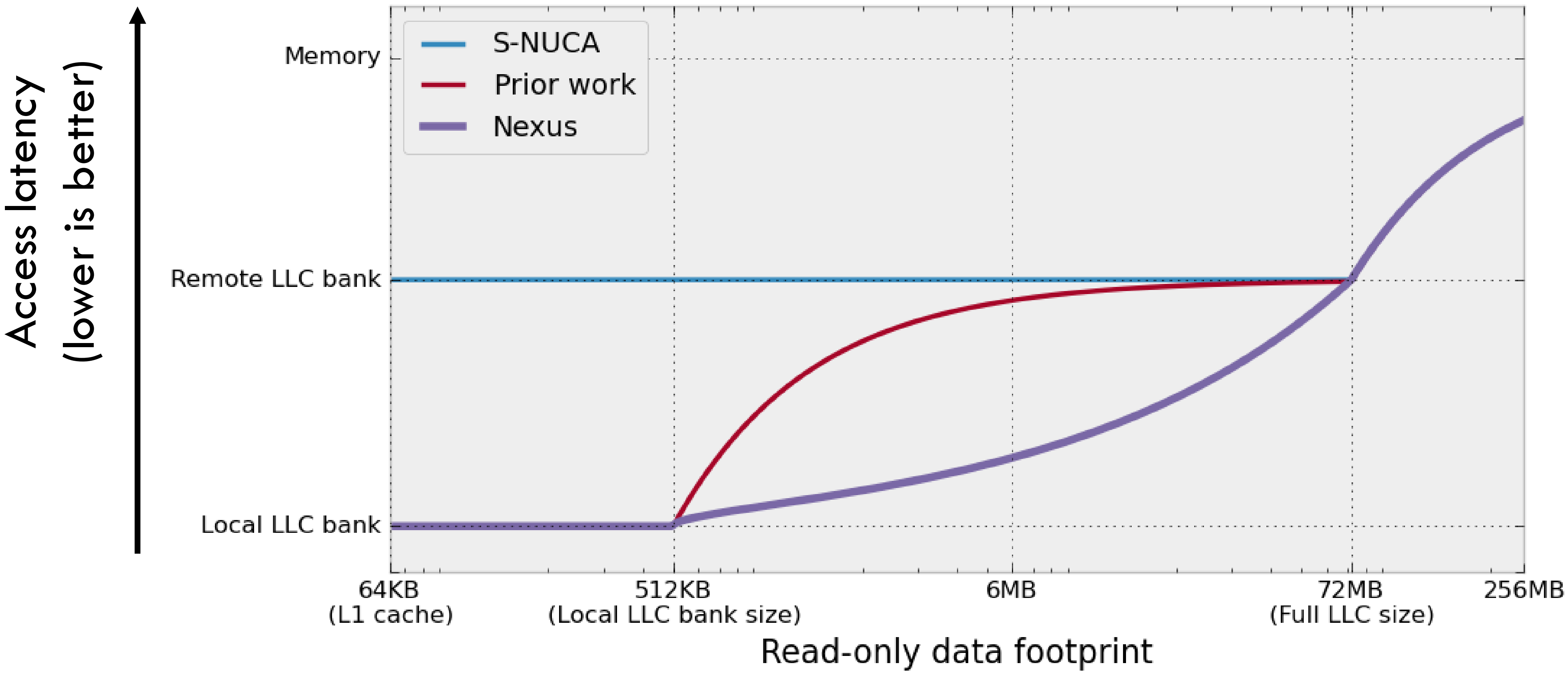


Data fits in the local bank

Some data is replicated in the local bank, but most data stays remote

Nexus allows replication even when read-only data cannot fit in the local bank



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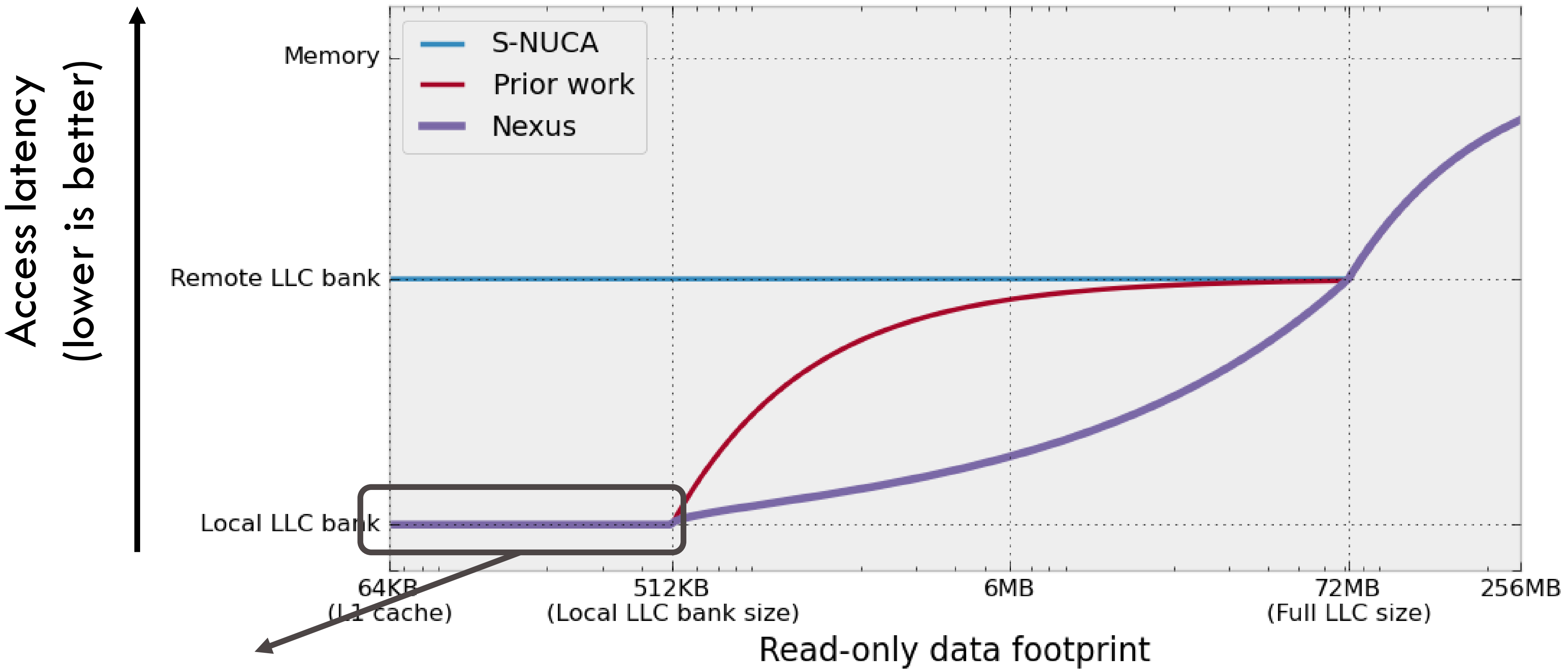

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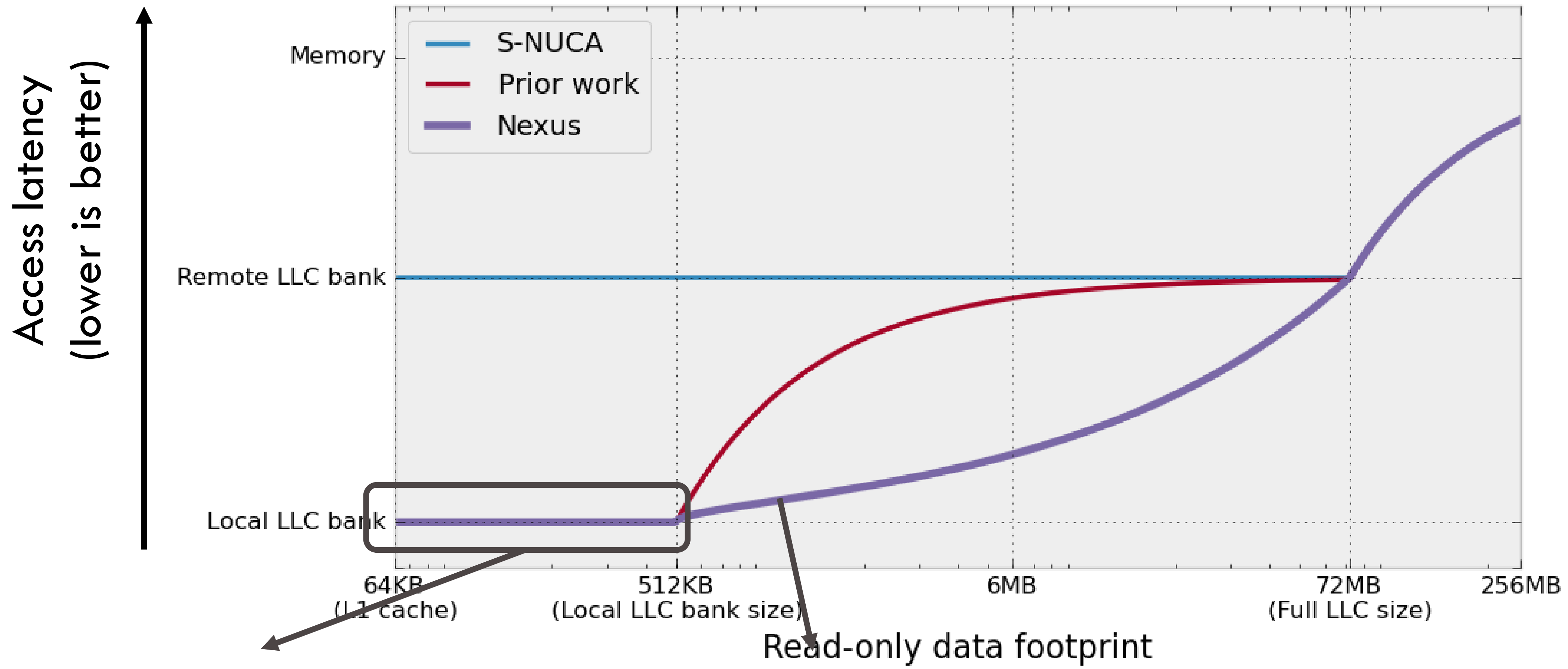

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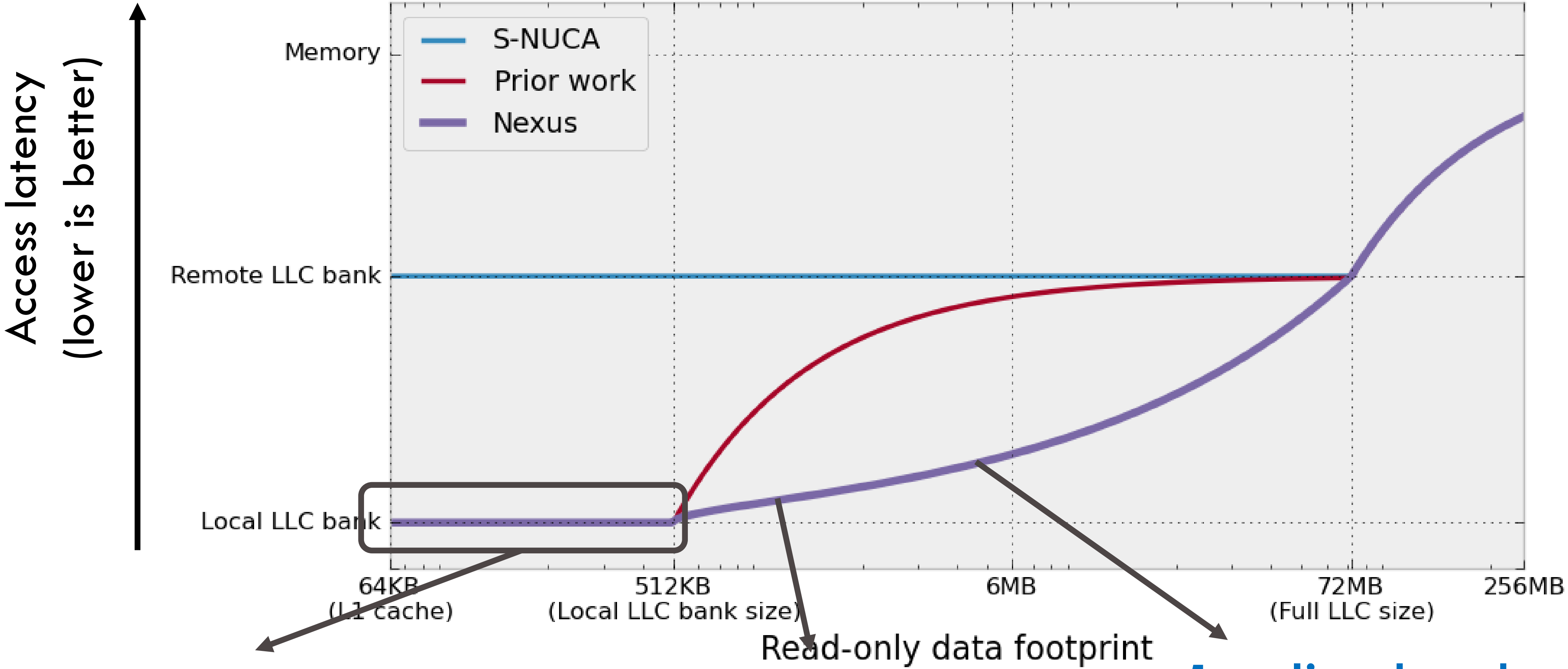

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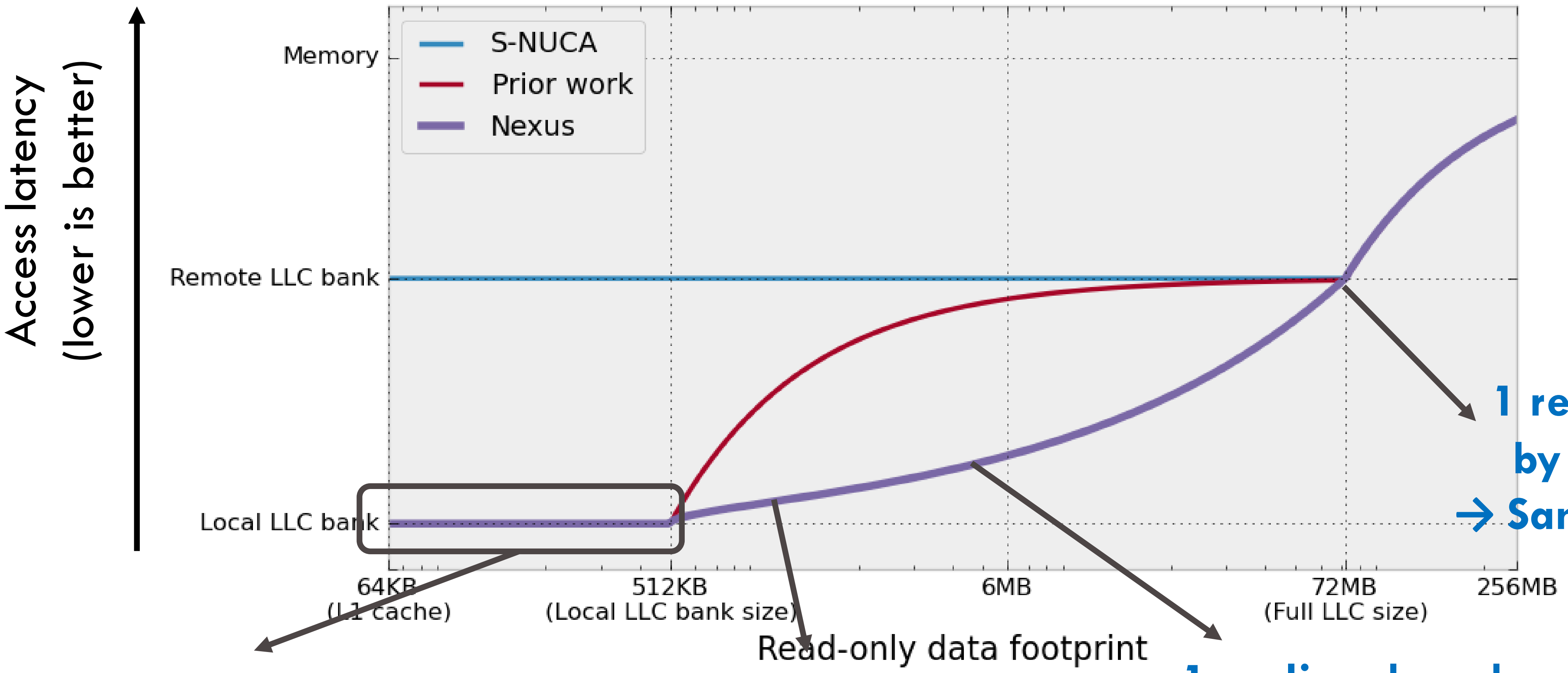

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1 replica shared by all threads → Same as S-NUCA

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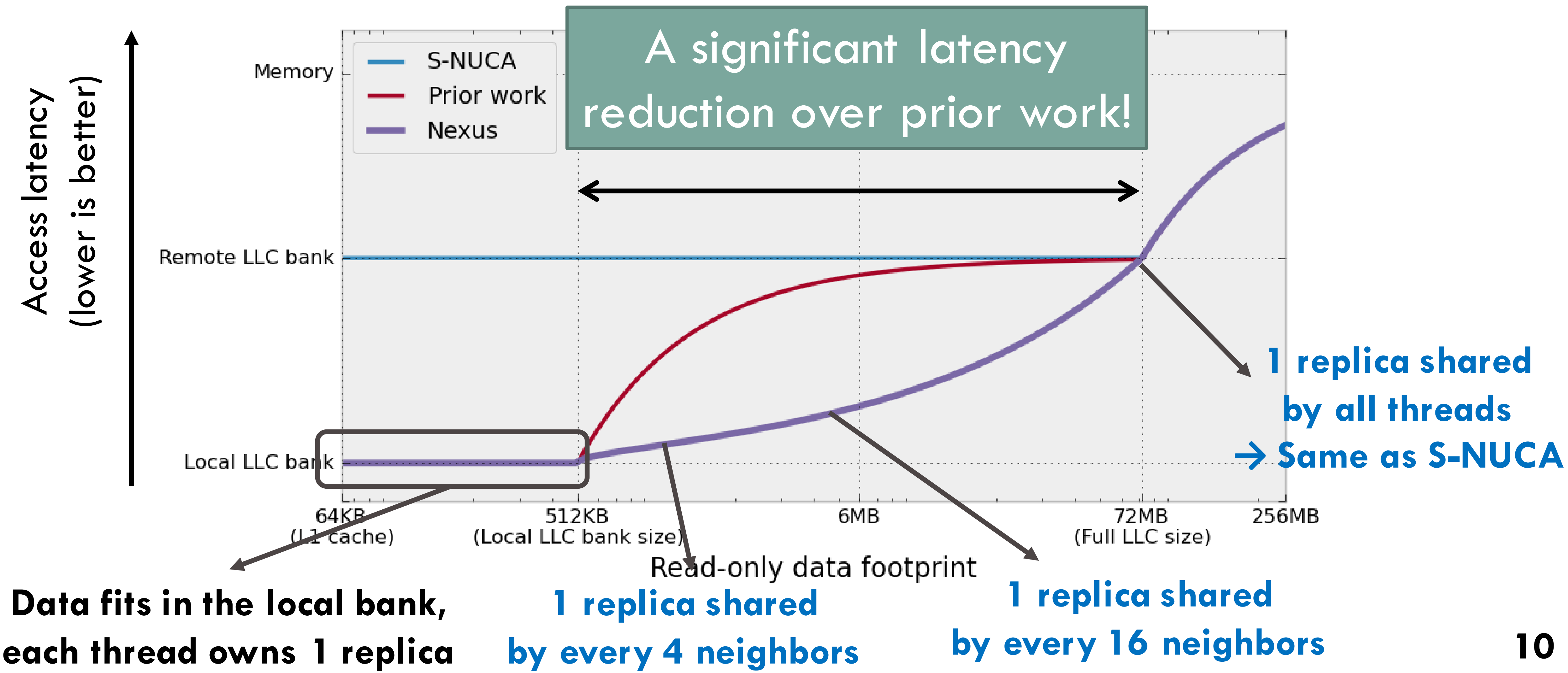
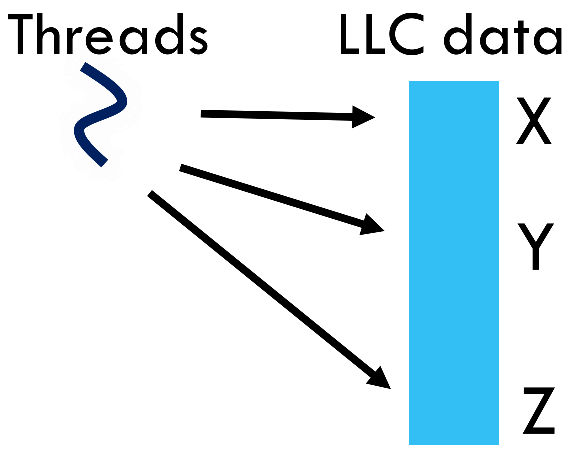
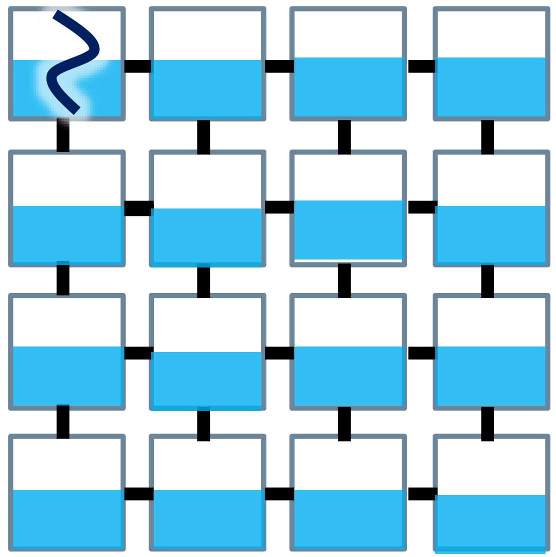


Recent directory-less dynamic NUCAs enable replication beyond the local bank





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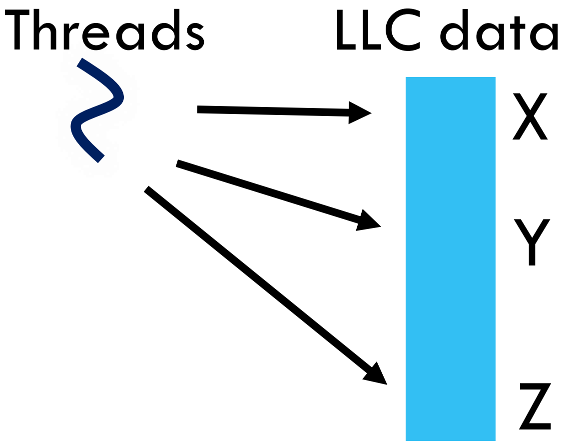
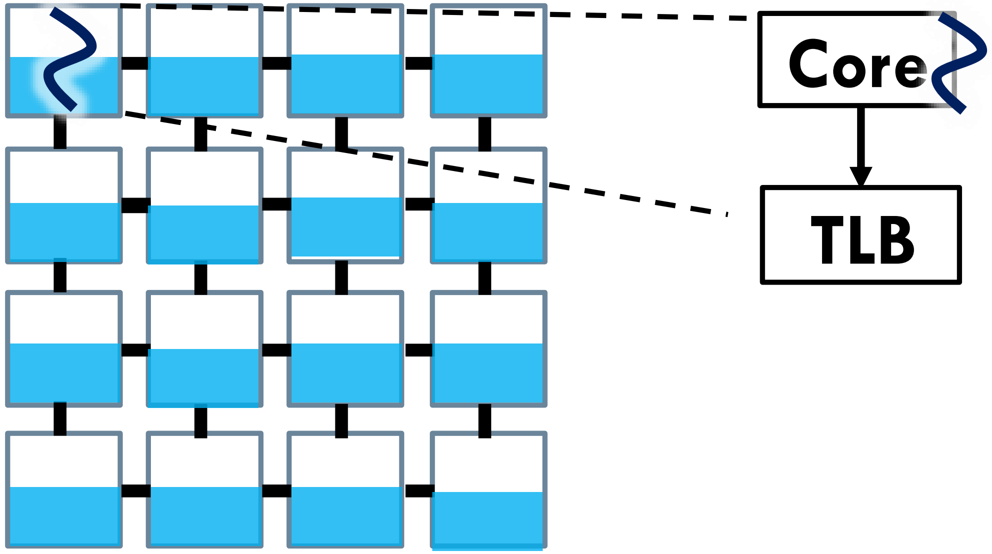
Data placement is controlled using the virtual memory system and does not require a global directory





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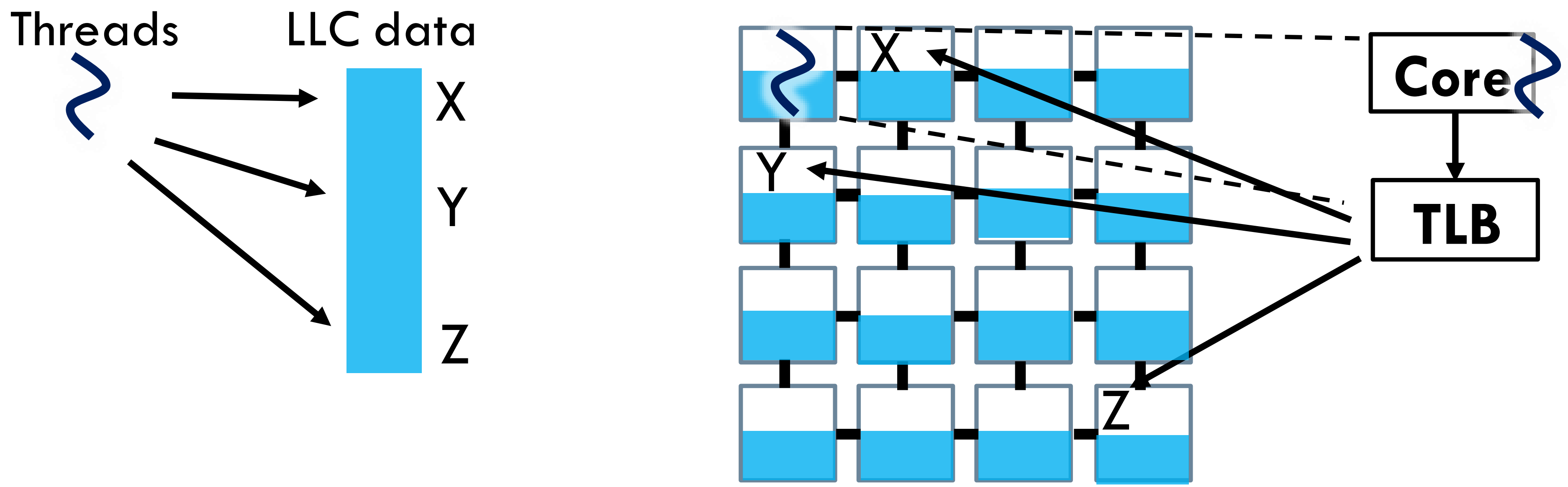

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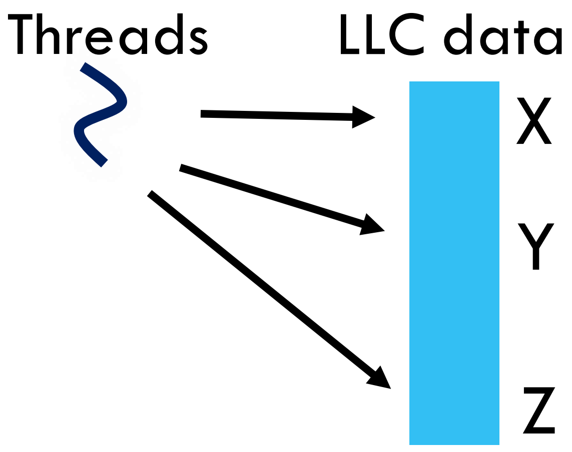
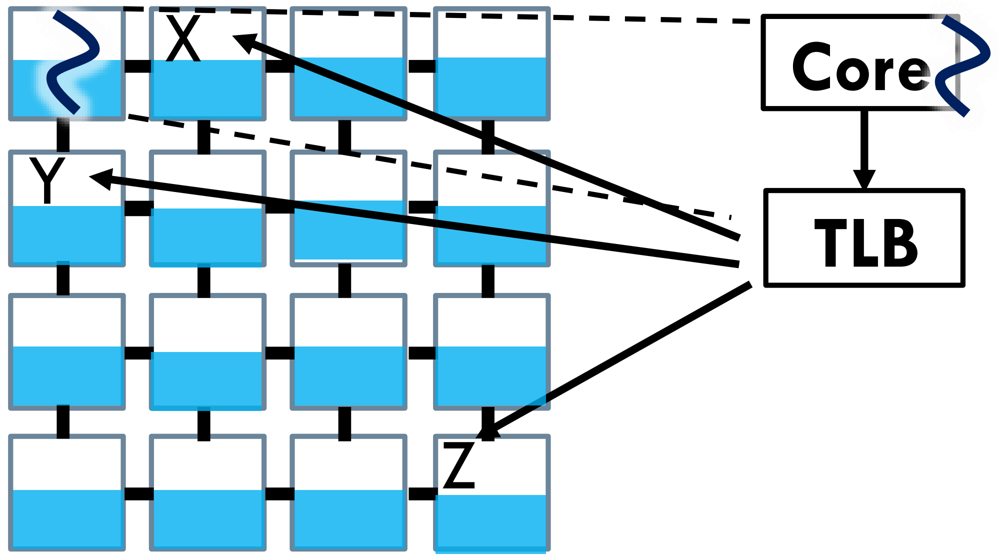
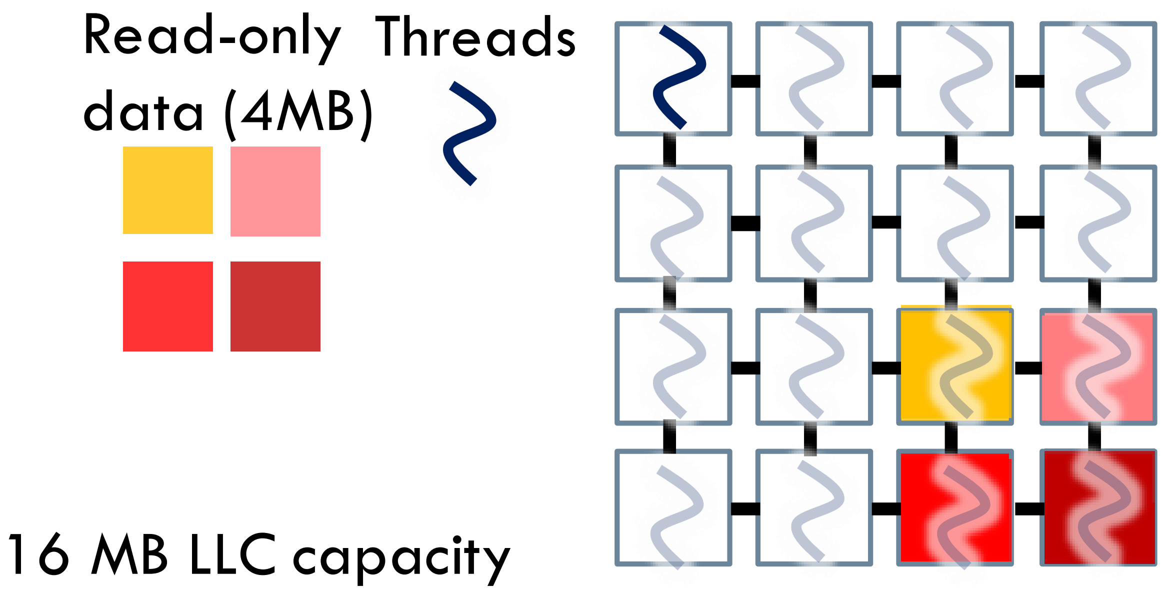




Data can be dynamically mapped to nearby banks and shared by arbitrary cores

The number of replicas (*replication degree*) is important



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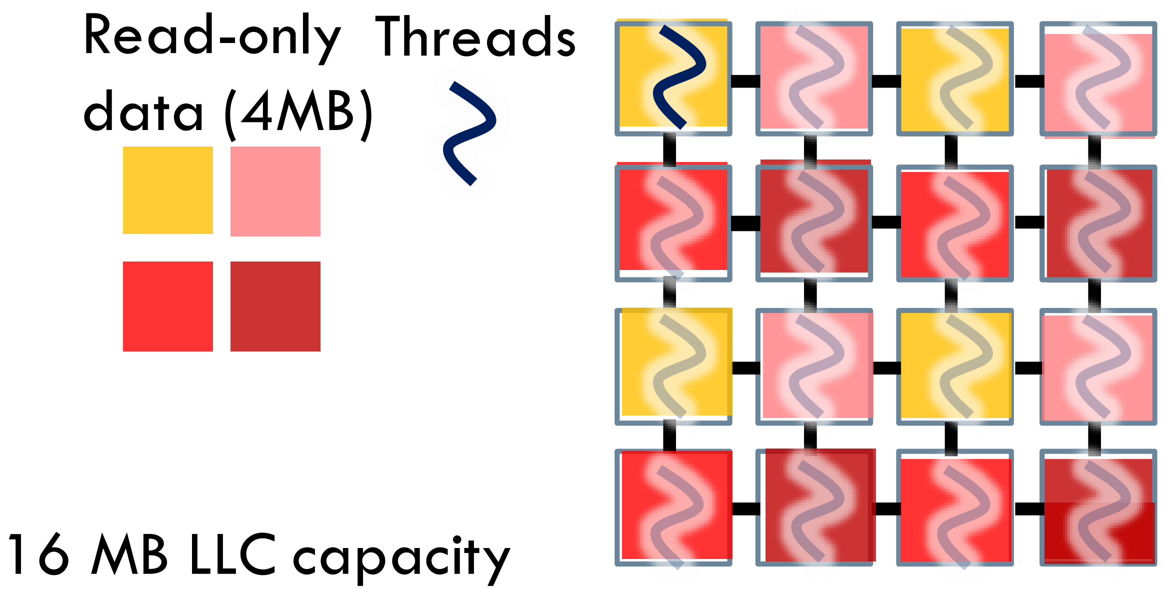

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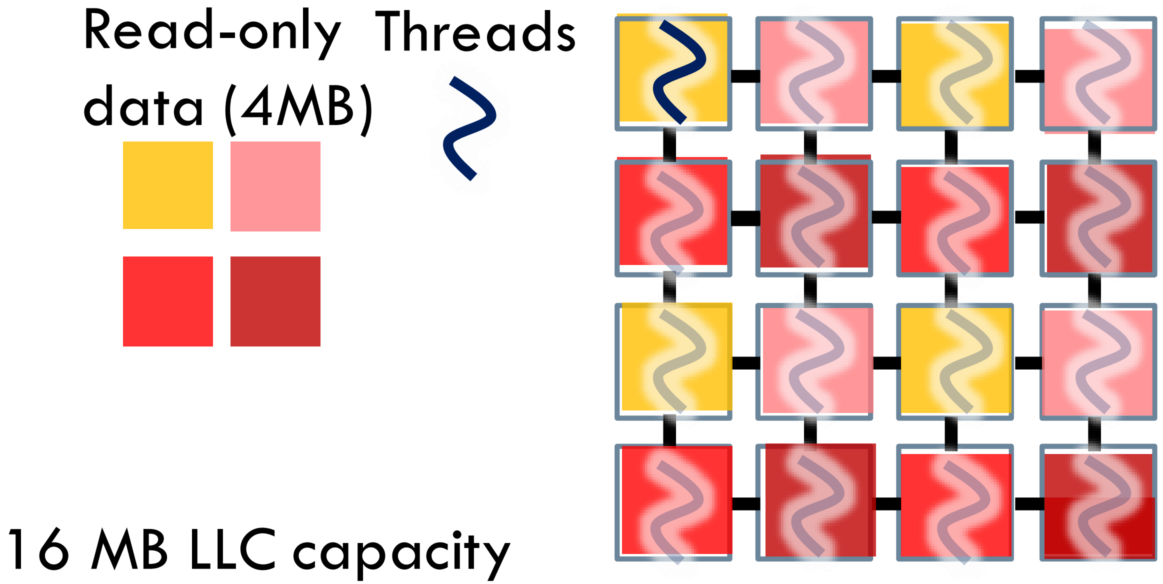
(4 x 4MB read-only = 16MB)



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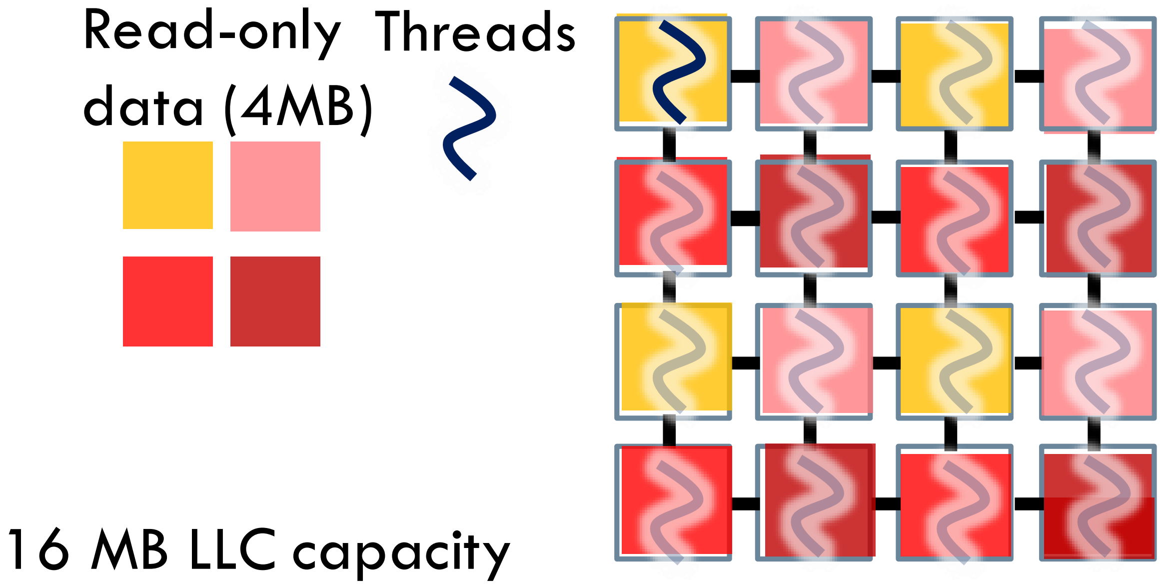


Choosing **how much** to replicate is more important than choosing **which lines** to replicate

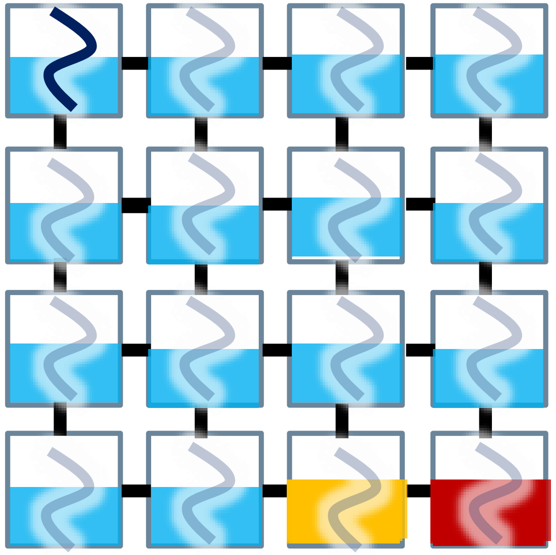
The number of replicas (*replication degree*) is important

Read-only data (1MB)

Threads

Other data (8MB)

16 MB LLC capacity



The number of replicas (*replication degree*) is important

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Threads

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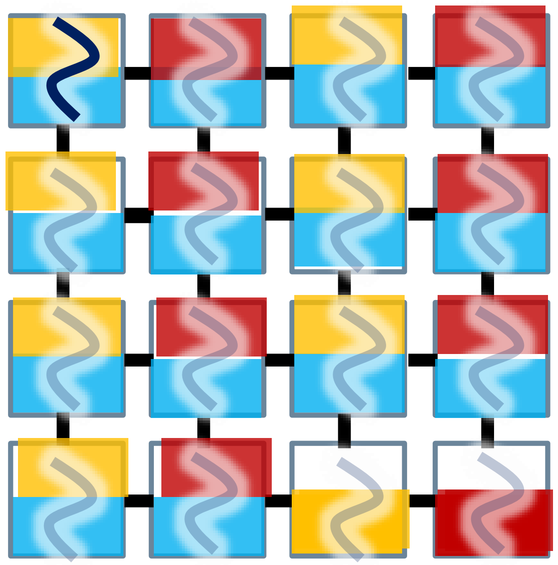

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(8 x 1MB read-only + 8MB other = 16MB)

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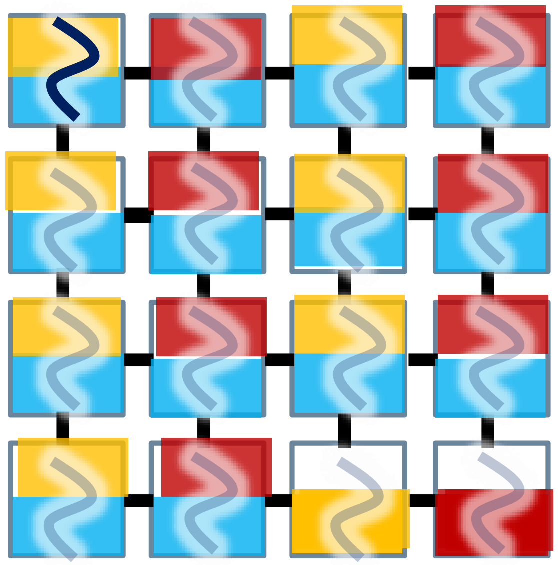

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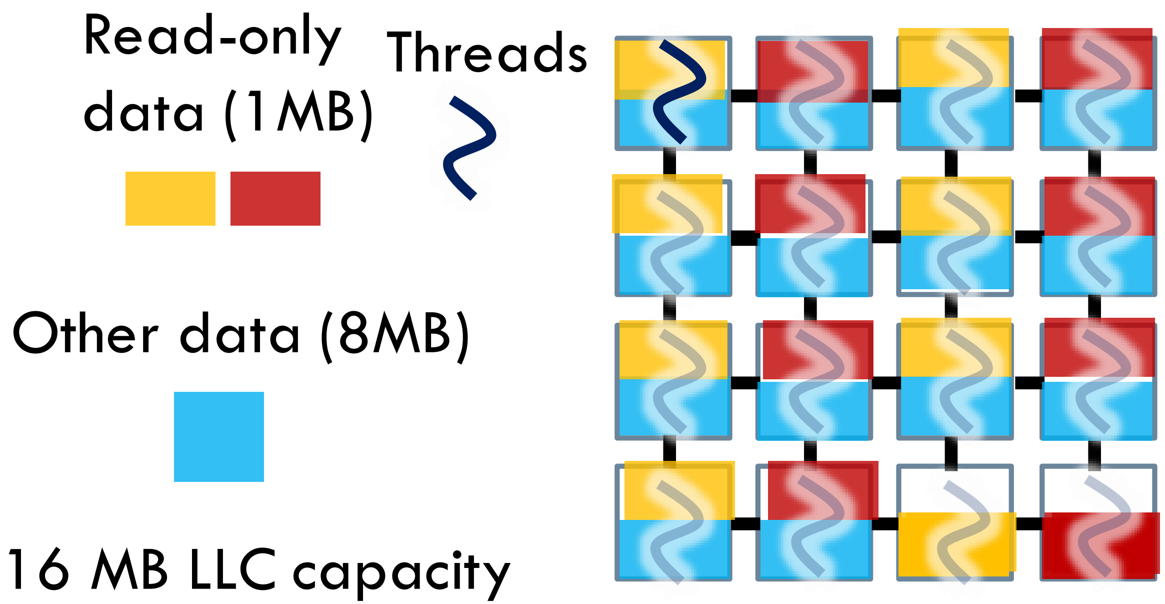
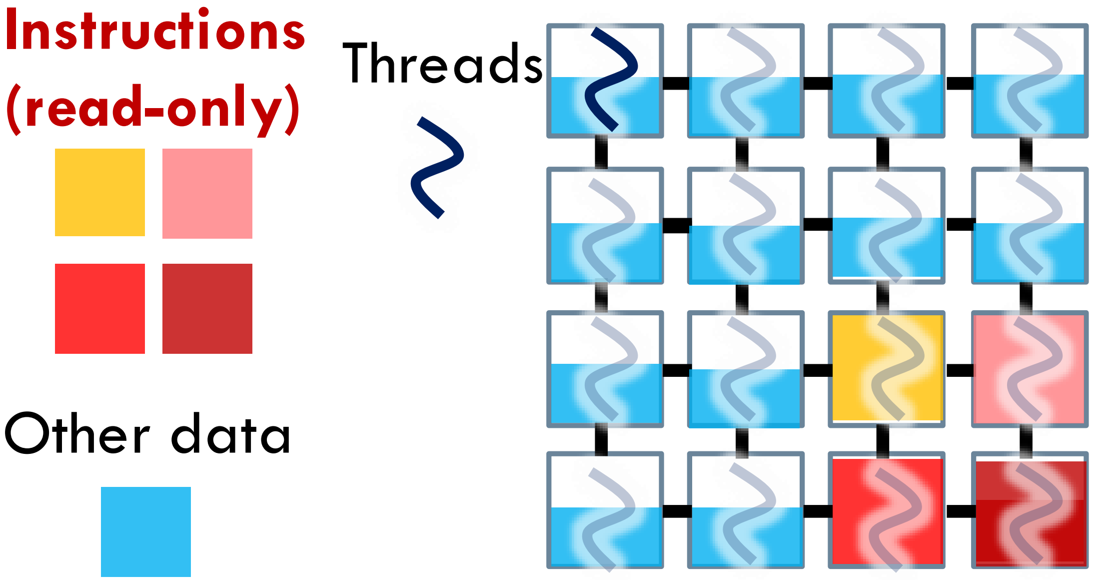


Too few replicas cause extra network traversals, while too many cause unnecessary cache misses

No adaptive replication in directory-less D-NUCAs



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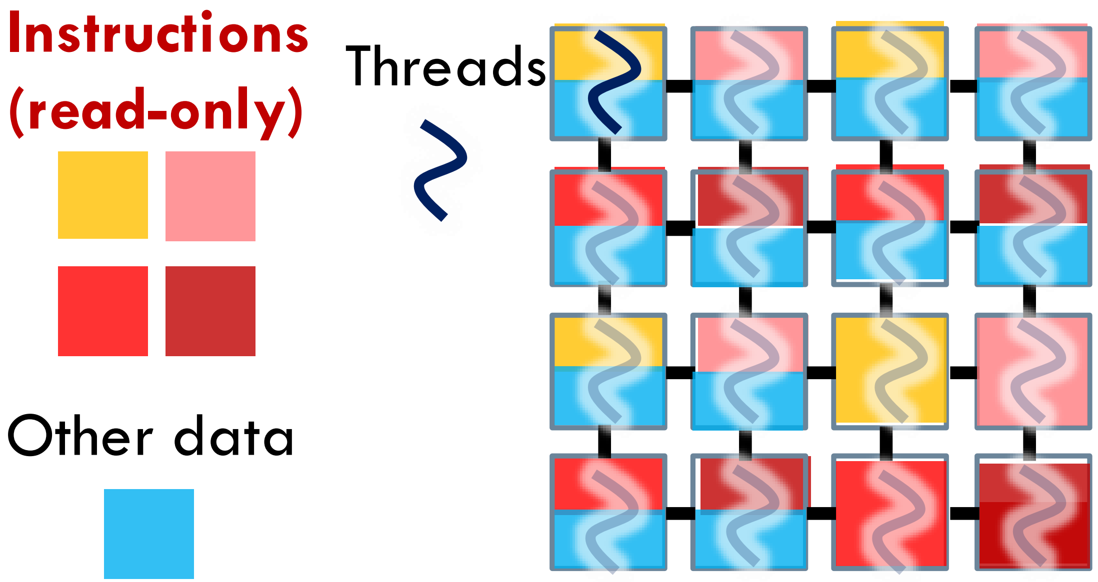

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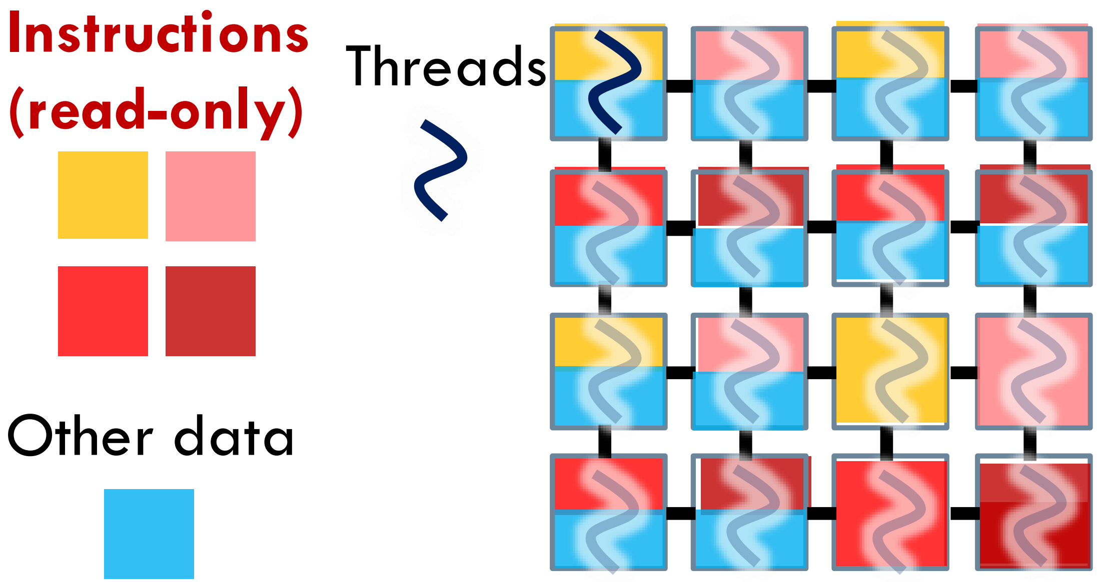
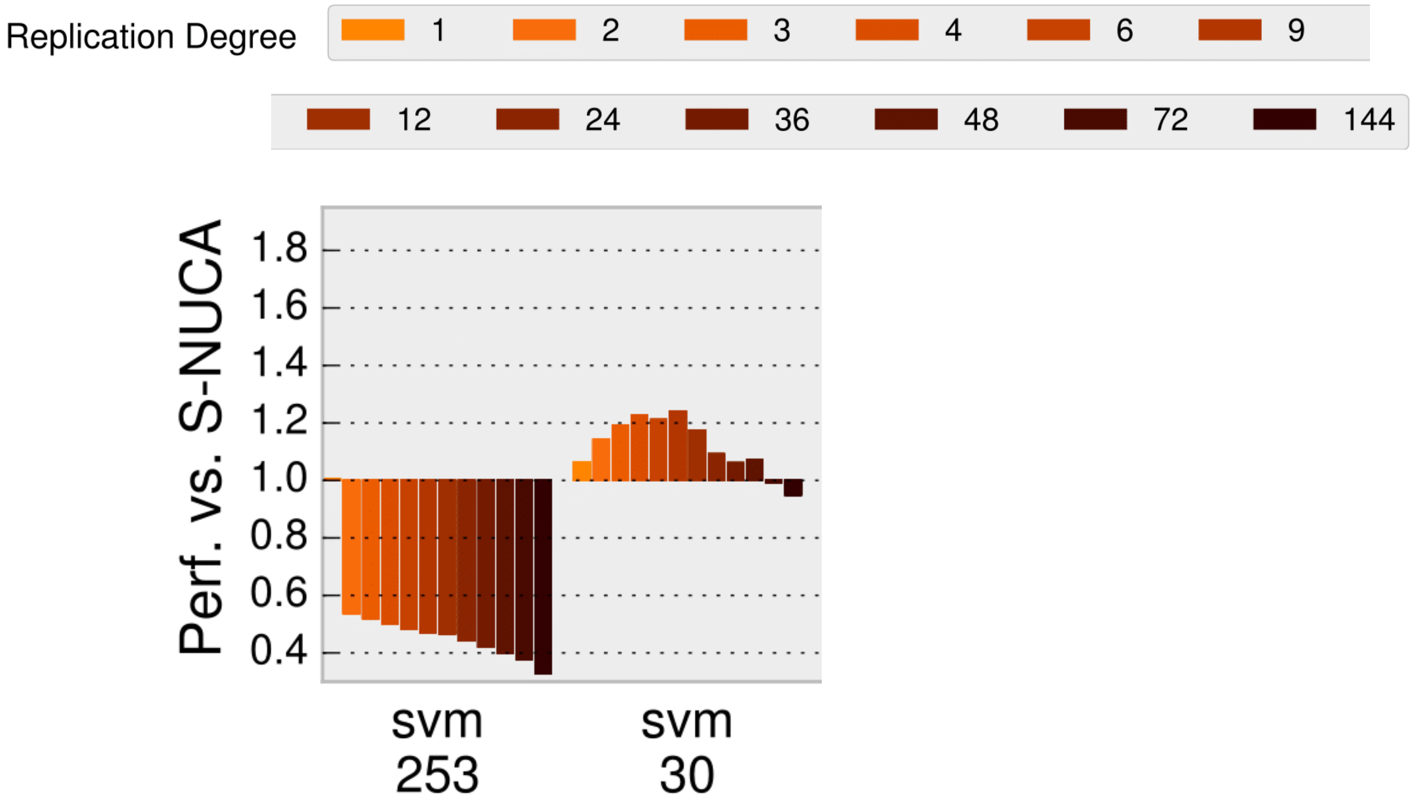


Other directory-less D-NUCAs do not replicate data

Workloads have different preferences to *replication degrees*

- Study read-only data intensive workloads running on a 144-core system
  - Apply different replication degrees for all read-only data



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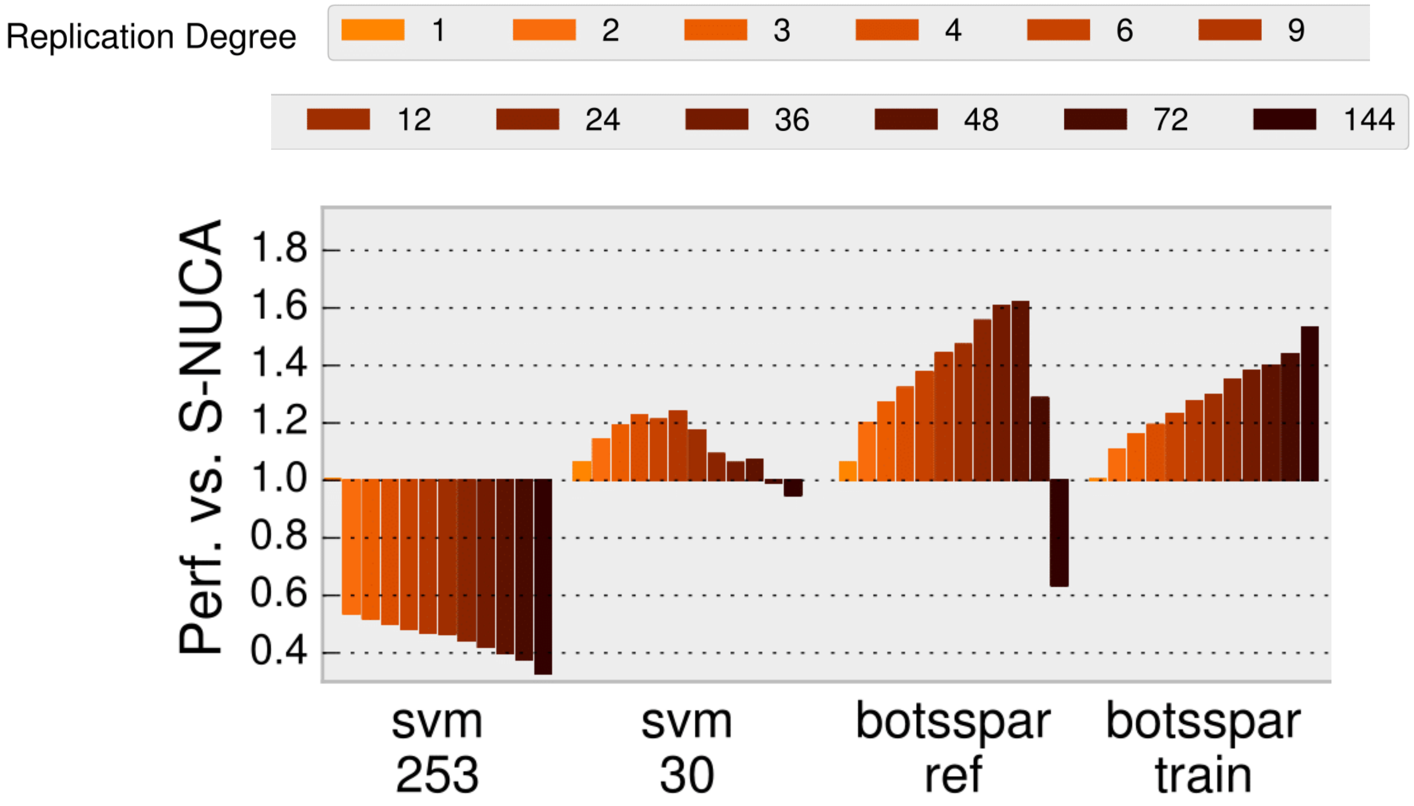

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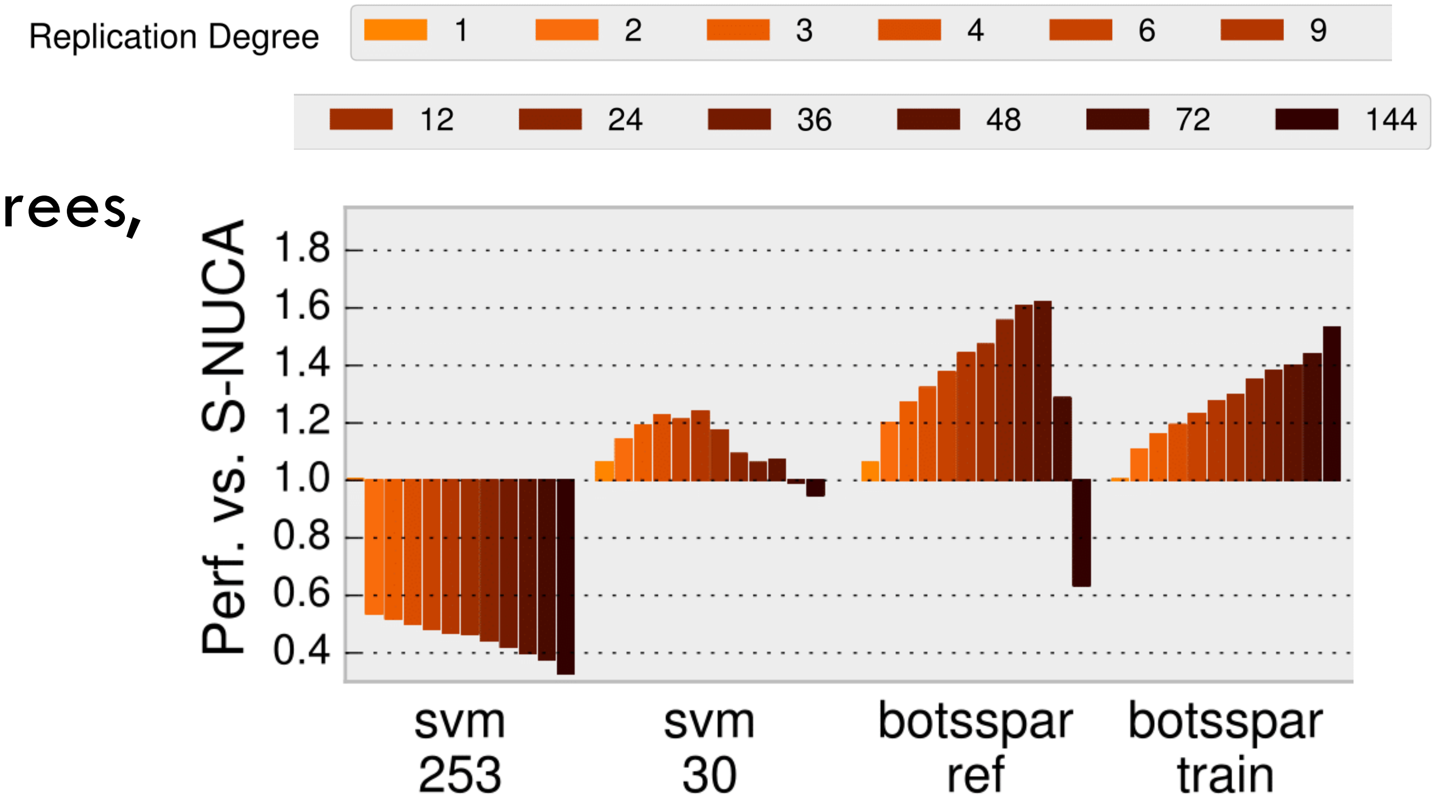

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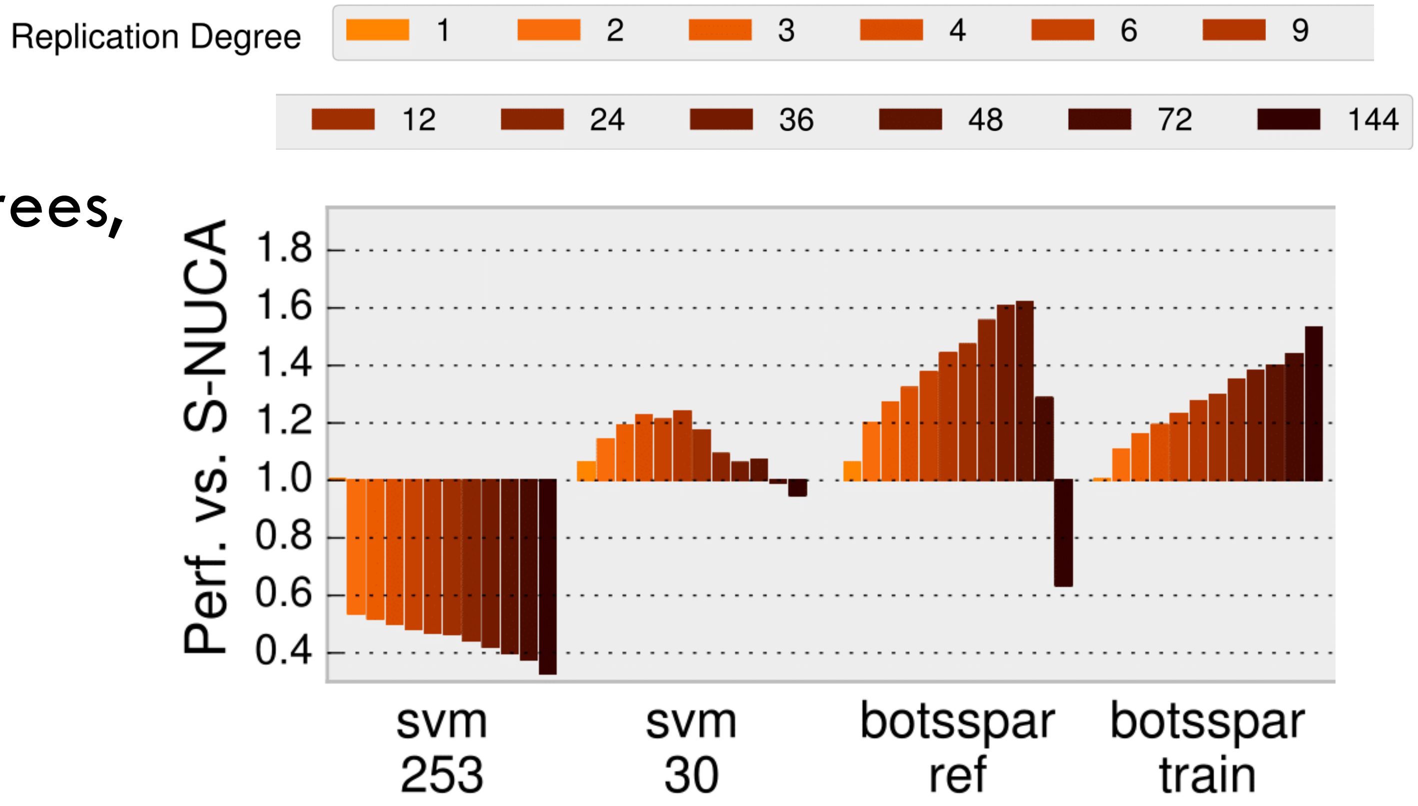
Observation 2:
A few replication degrees suffice.



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Focus of this talk

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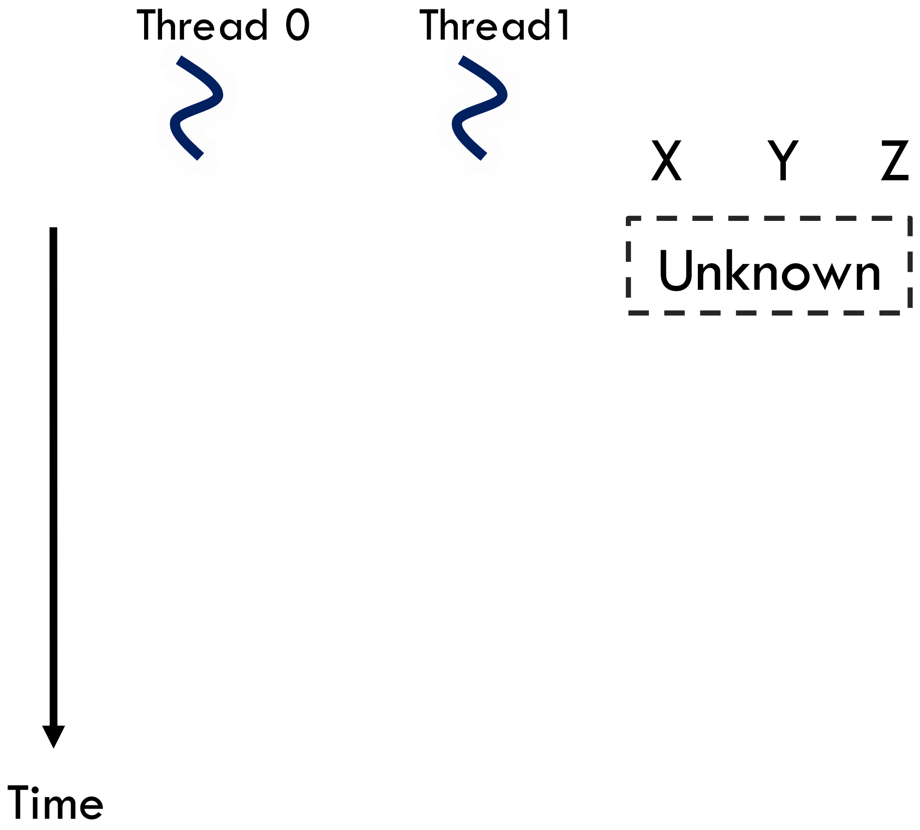

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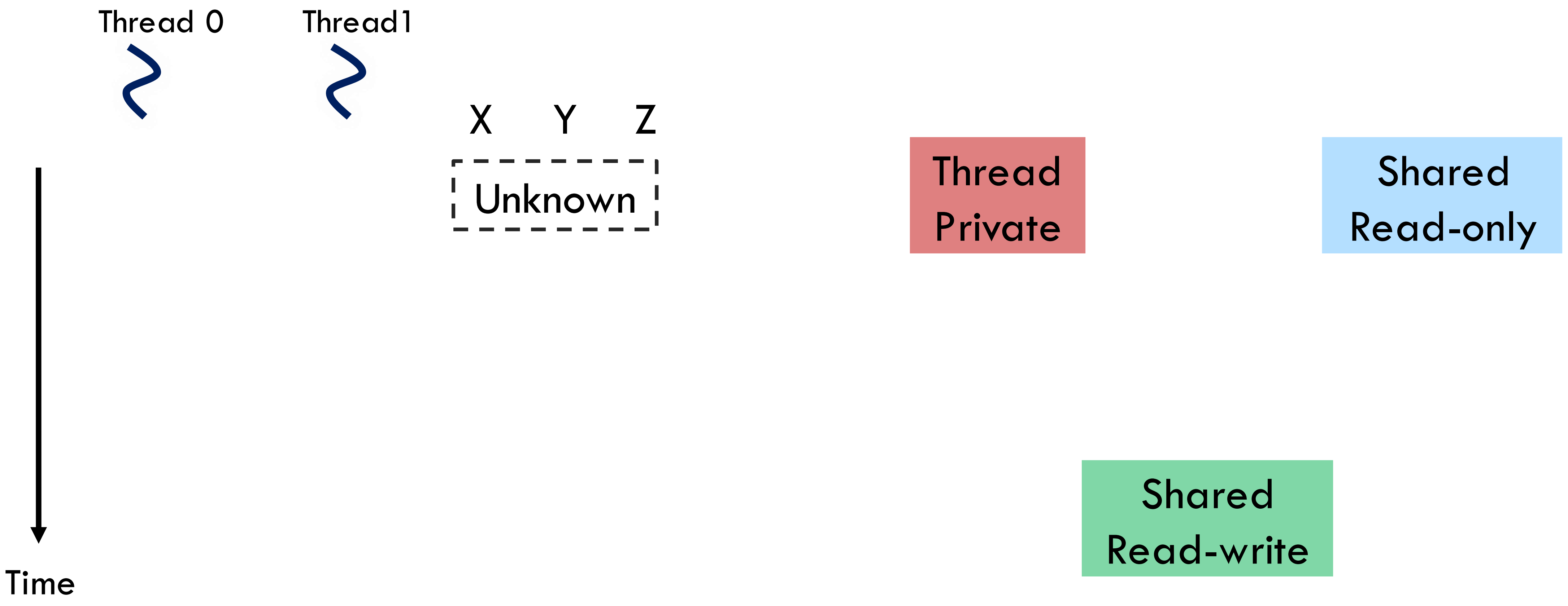

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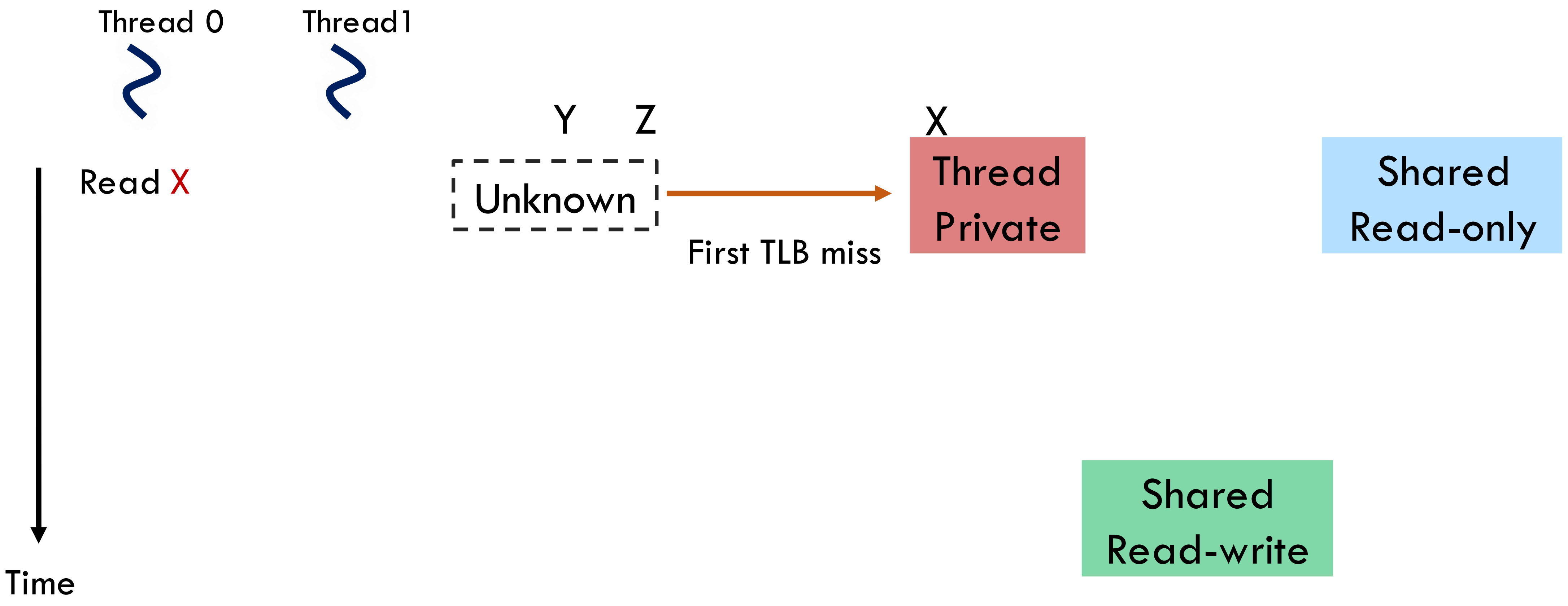

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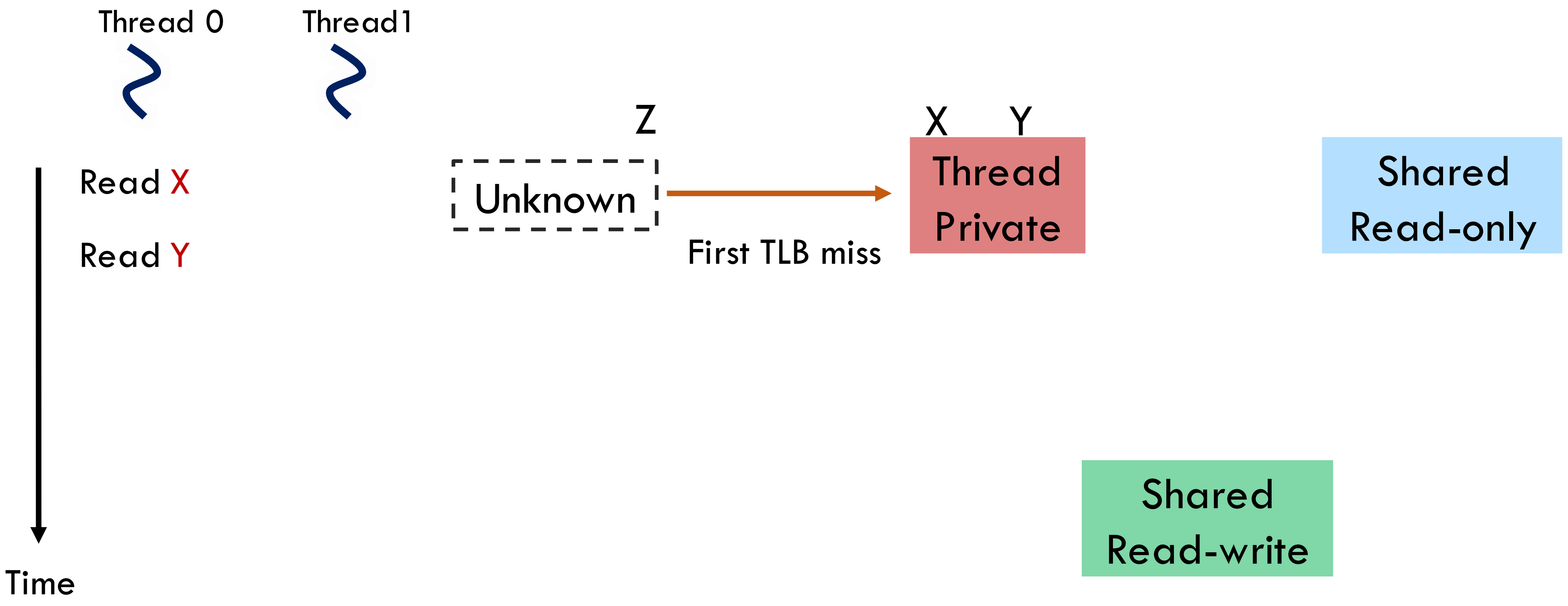

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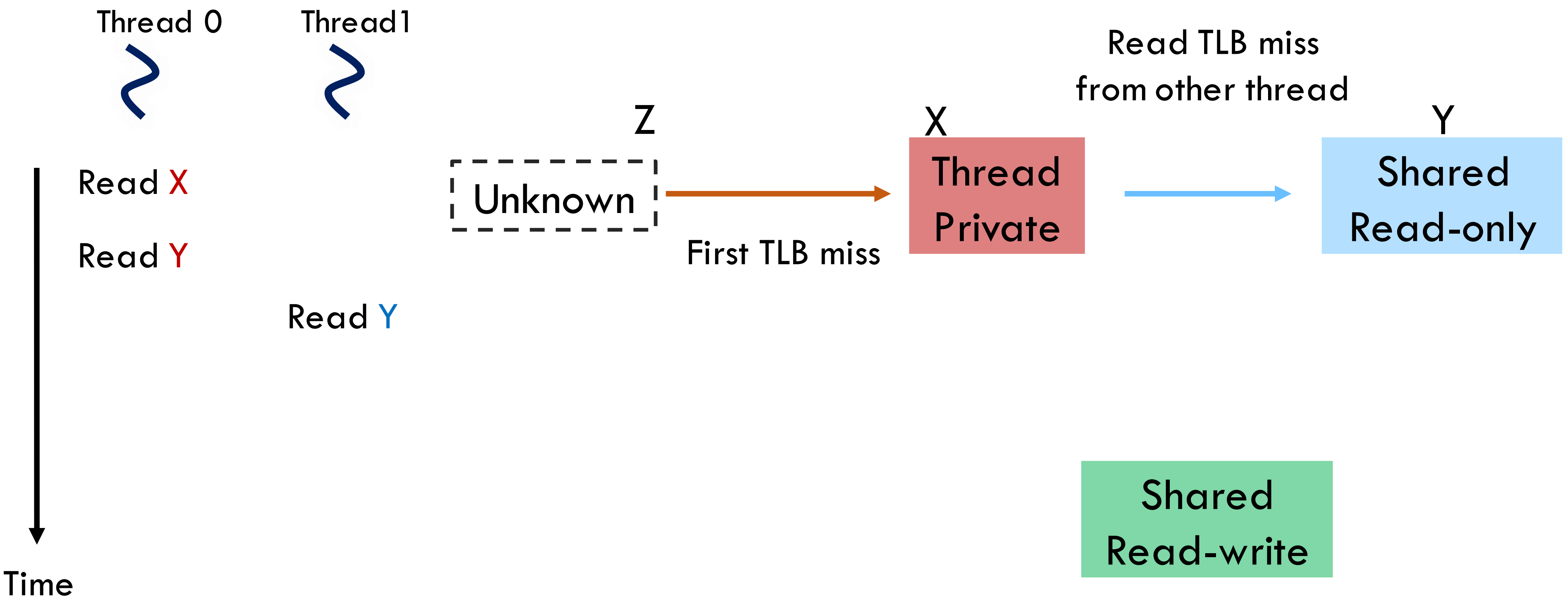

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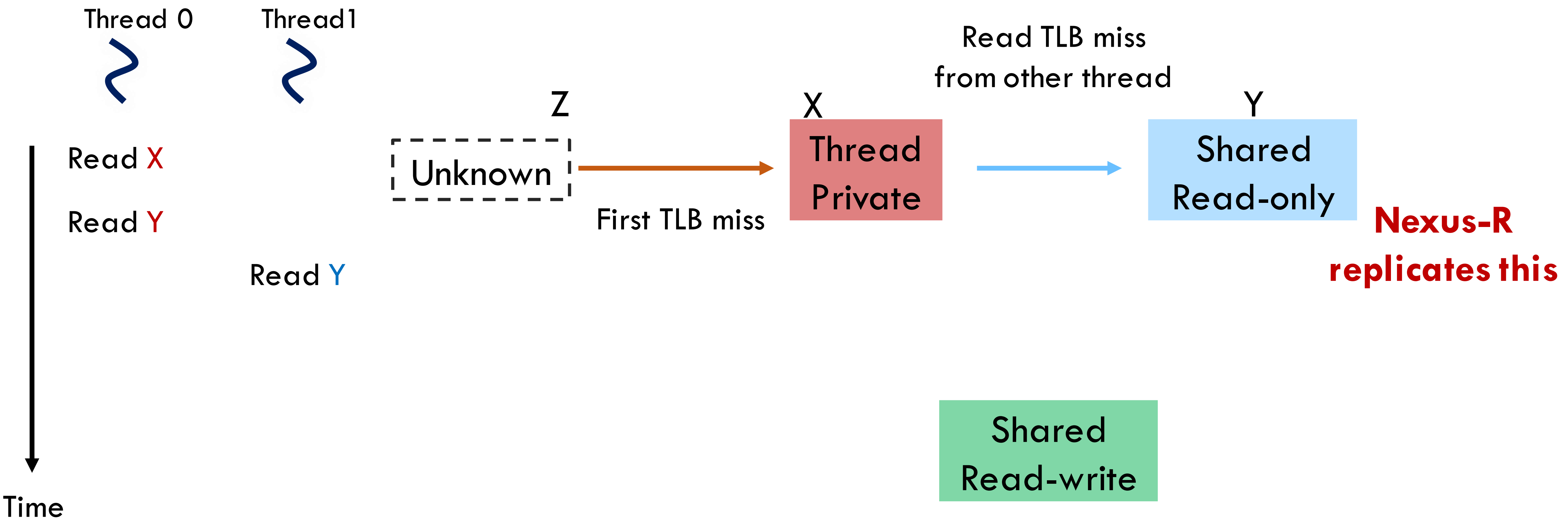

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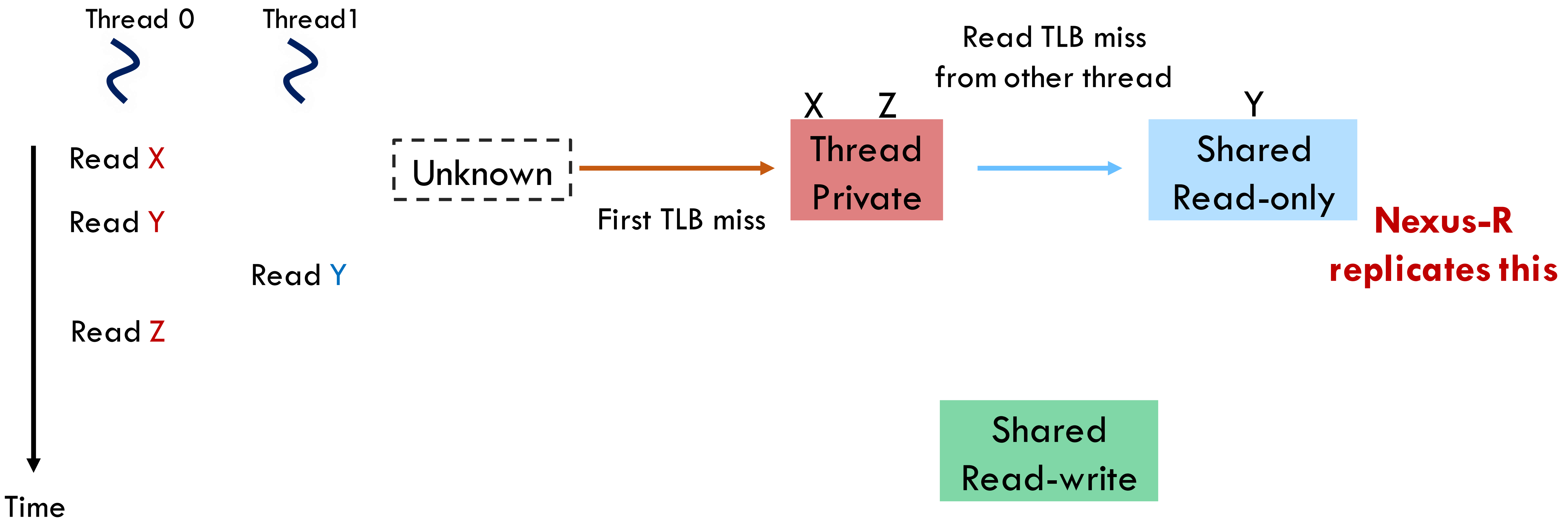

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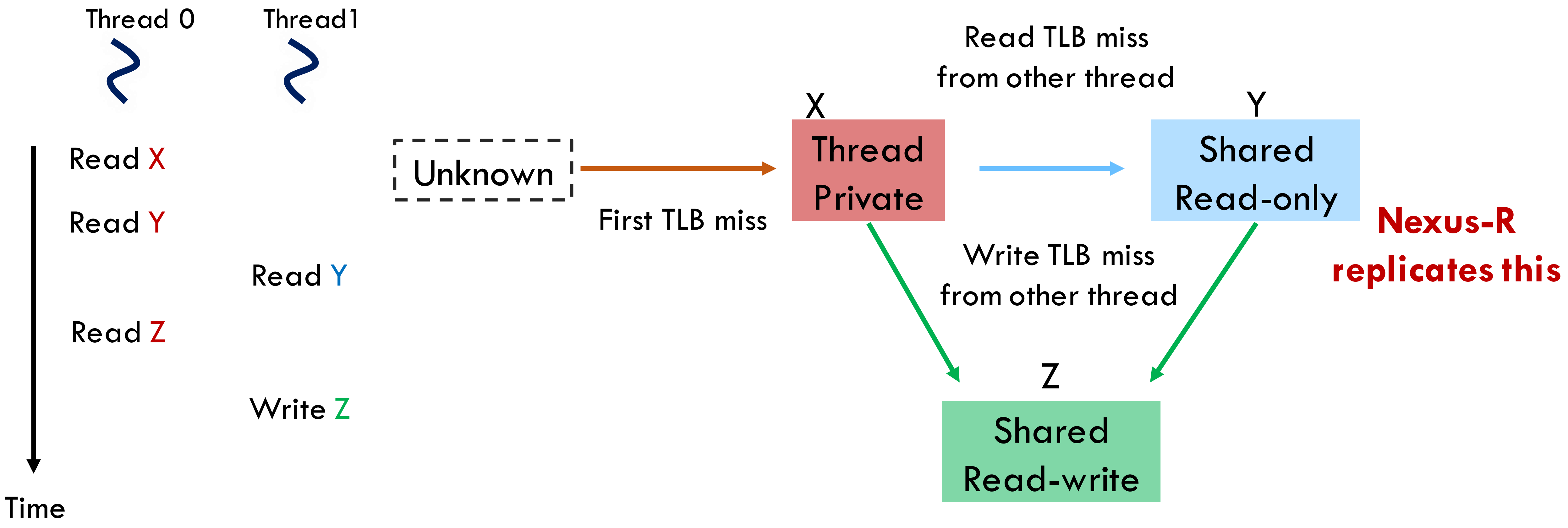

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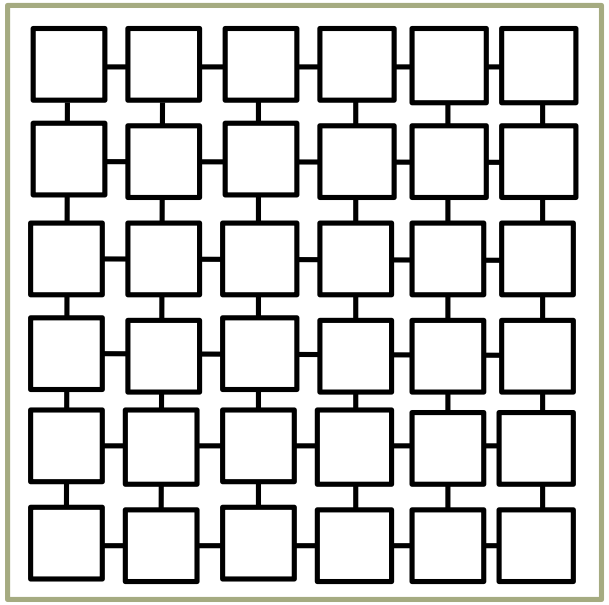

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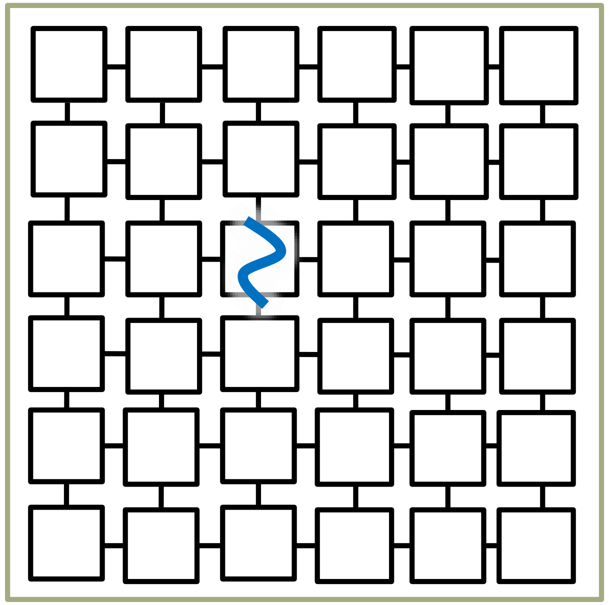

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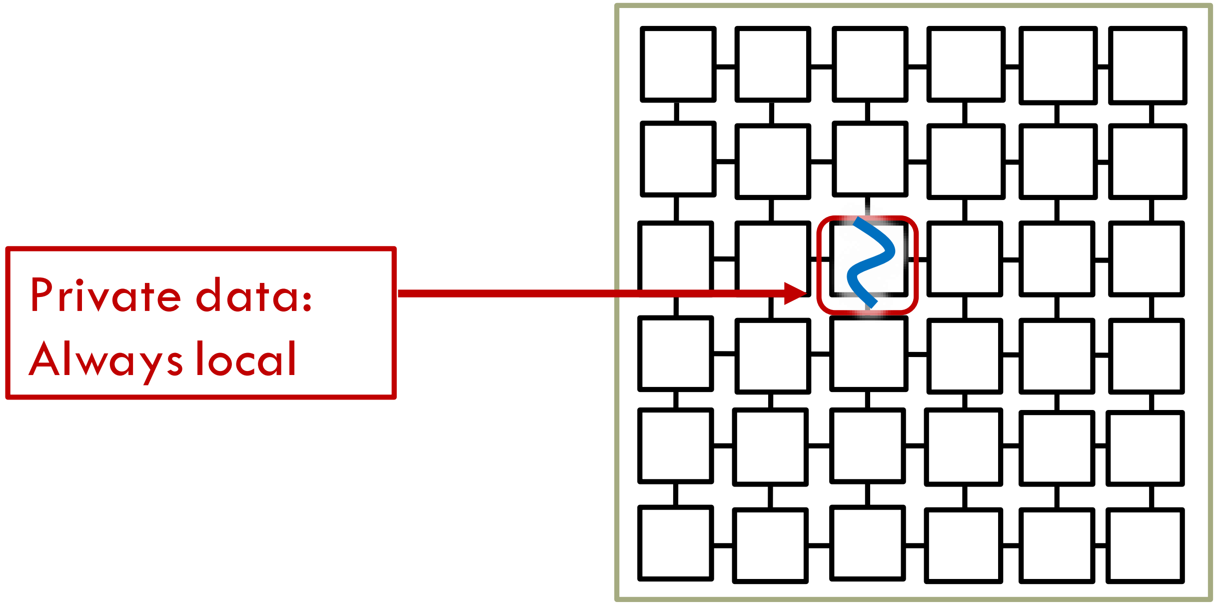

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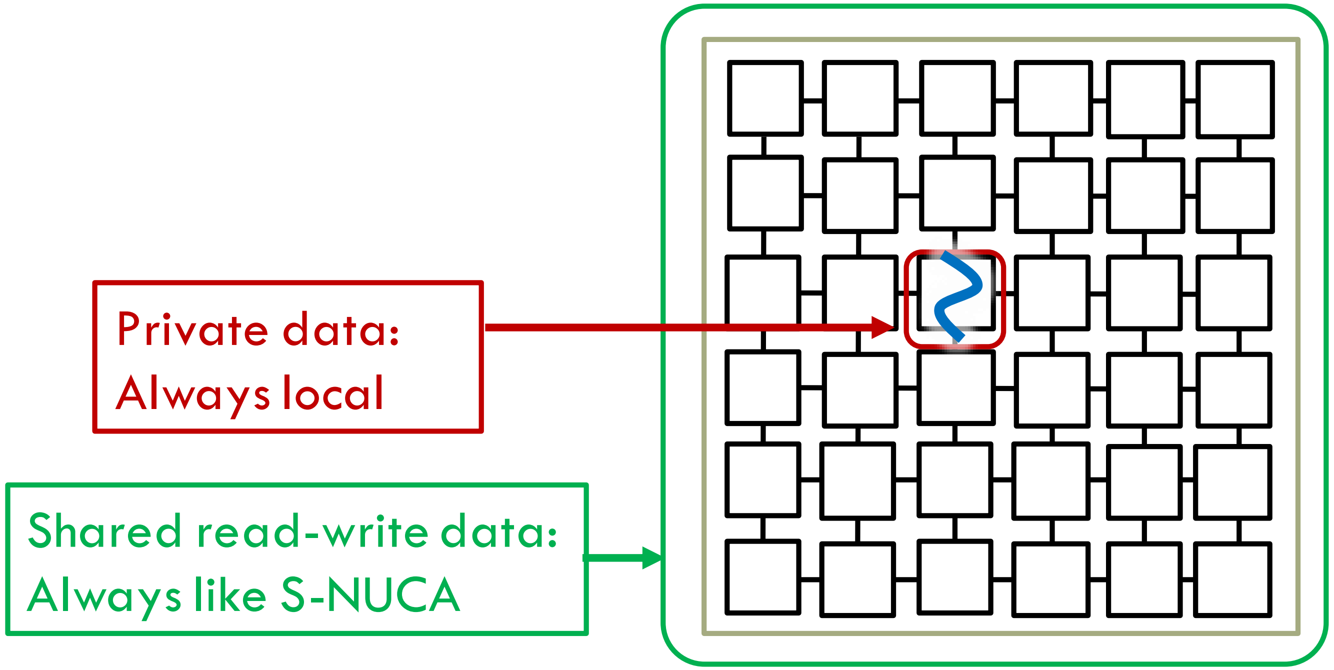

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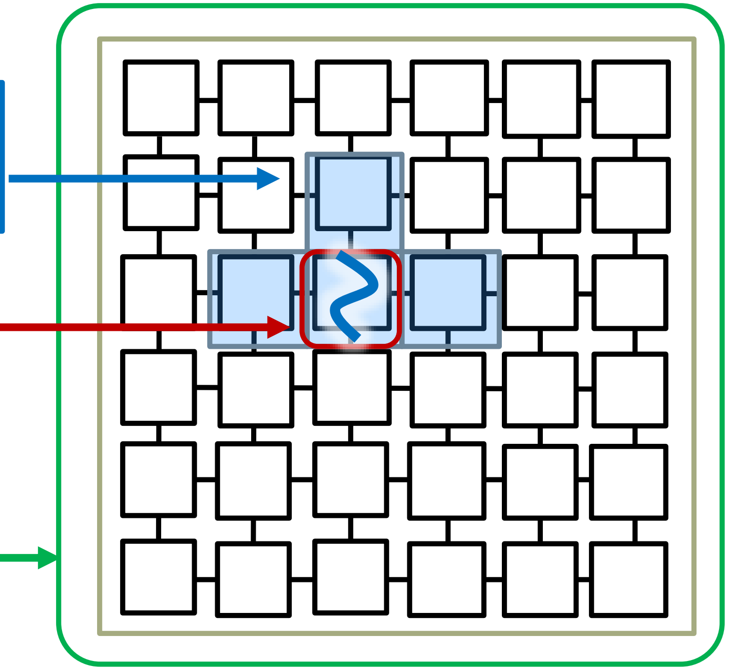
Replication **degree of 9 on 36 cores →**
cluster with **size of 4 (36 divided by 9)**

Shared read-only data:
Replicated clusters

Private data:
Always local

Shared read-write data:
Always like S-NUCA



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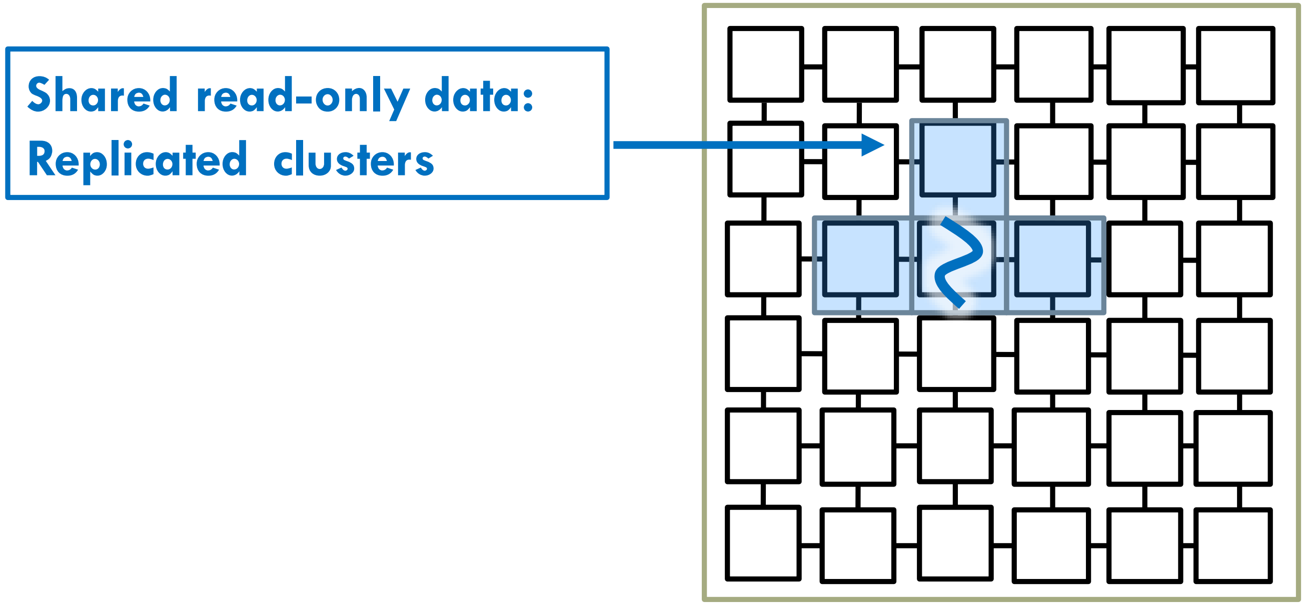

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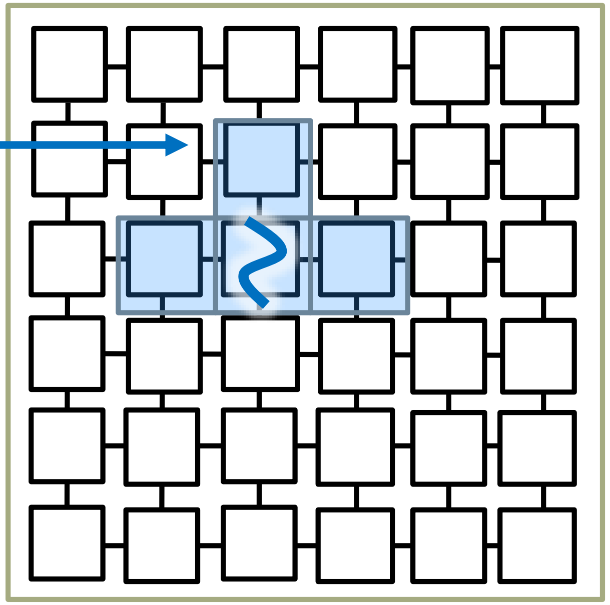

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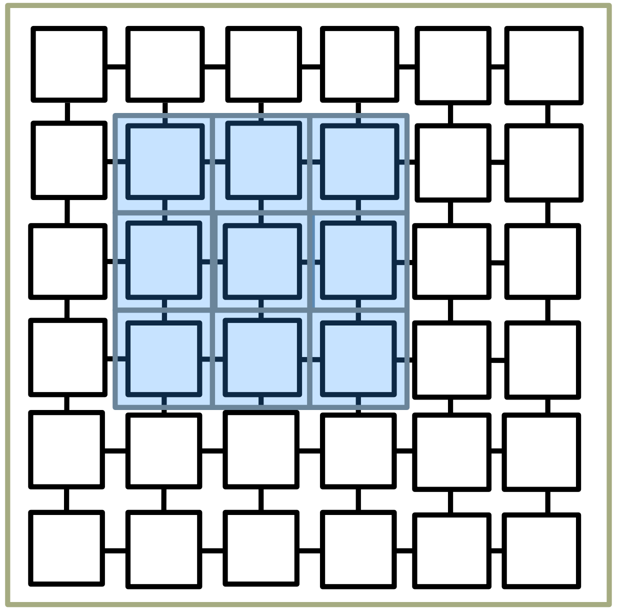

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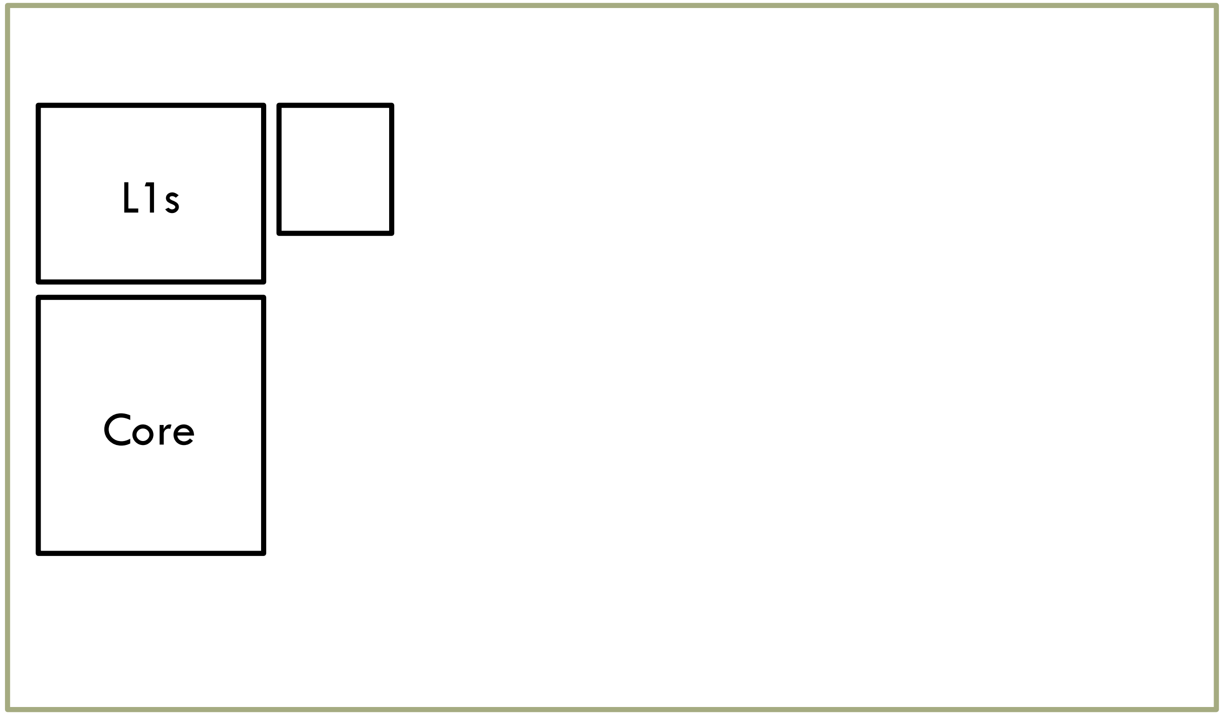

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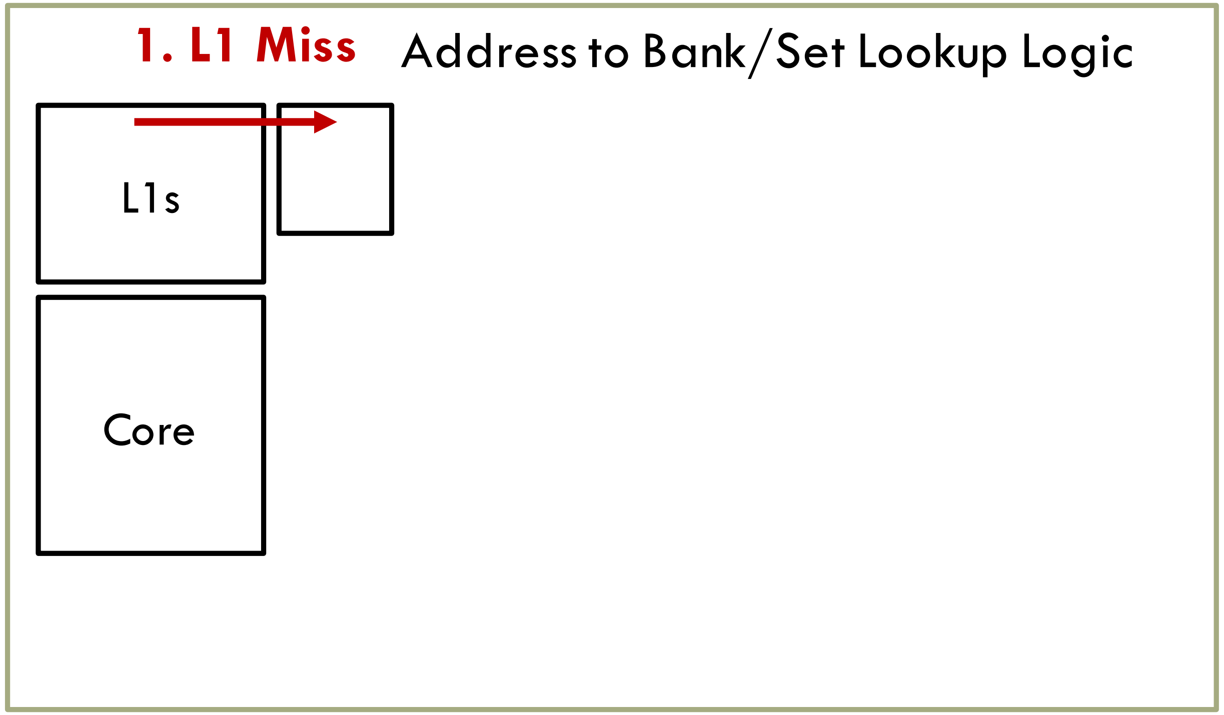

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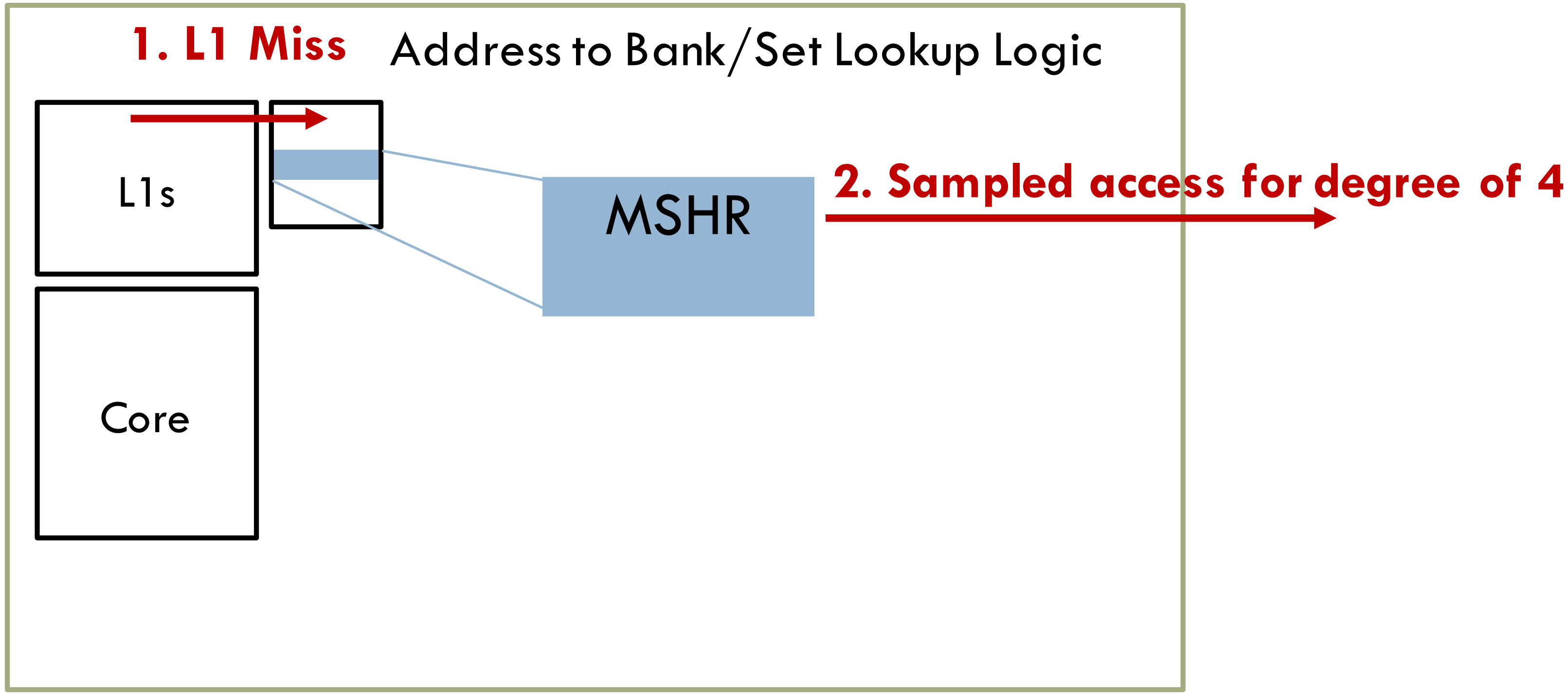

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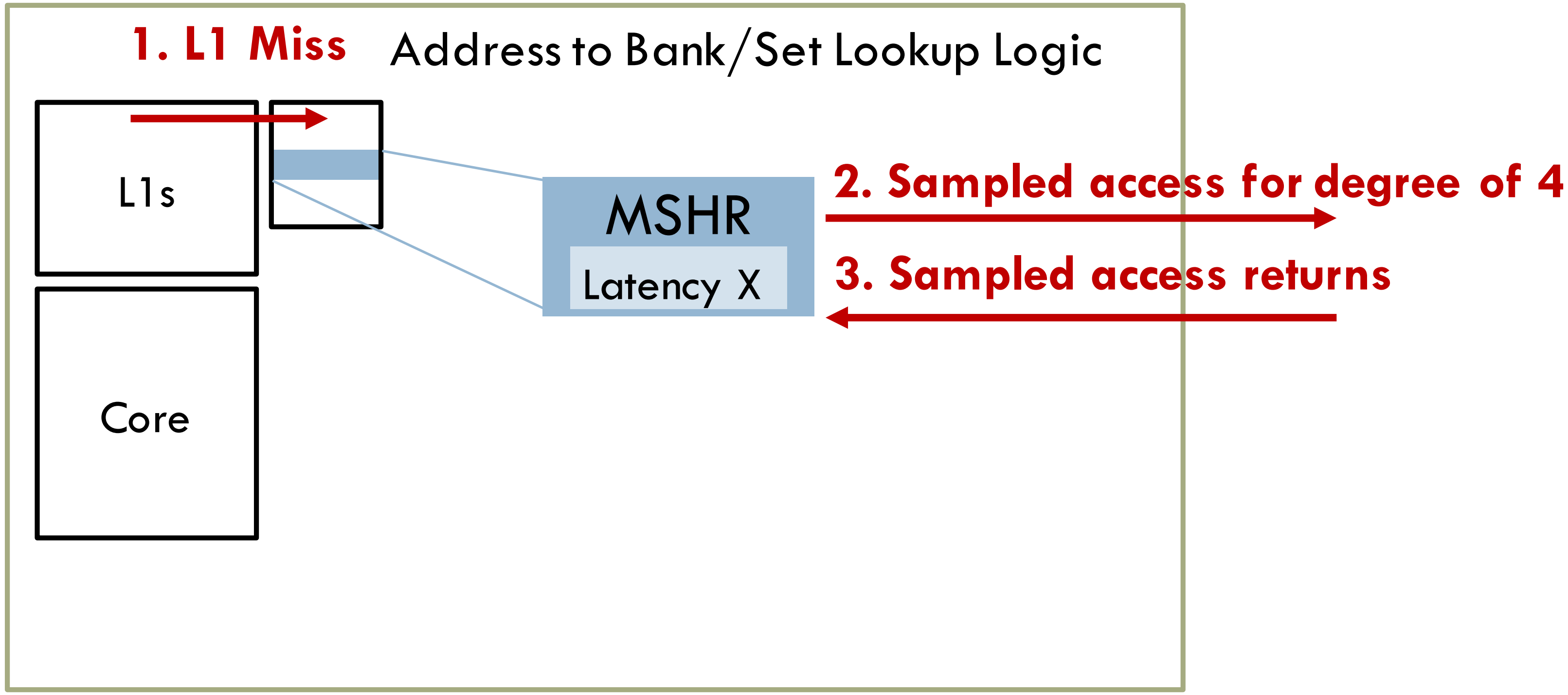

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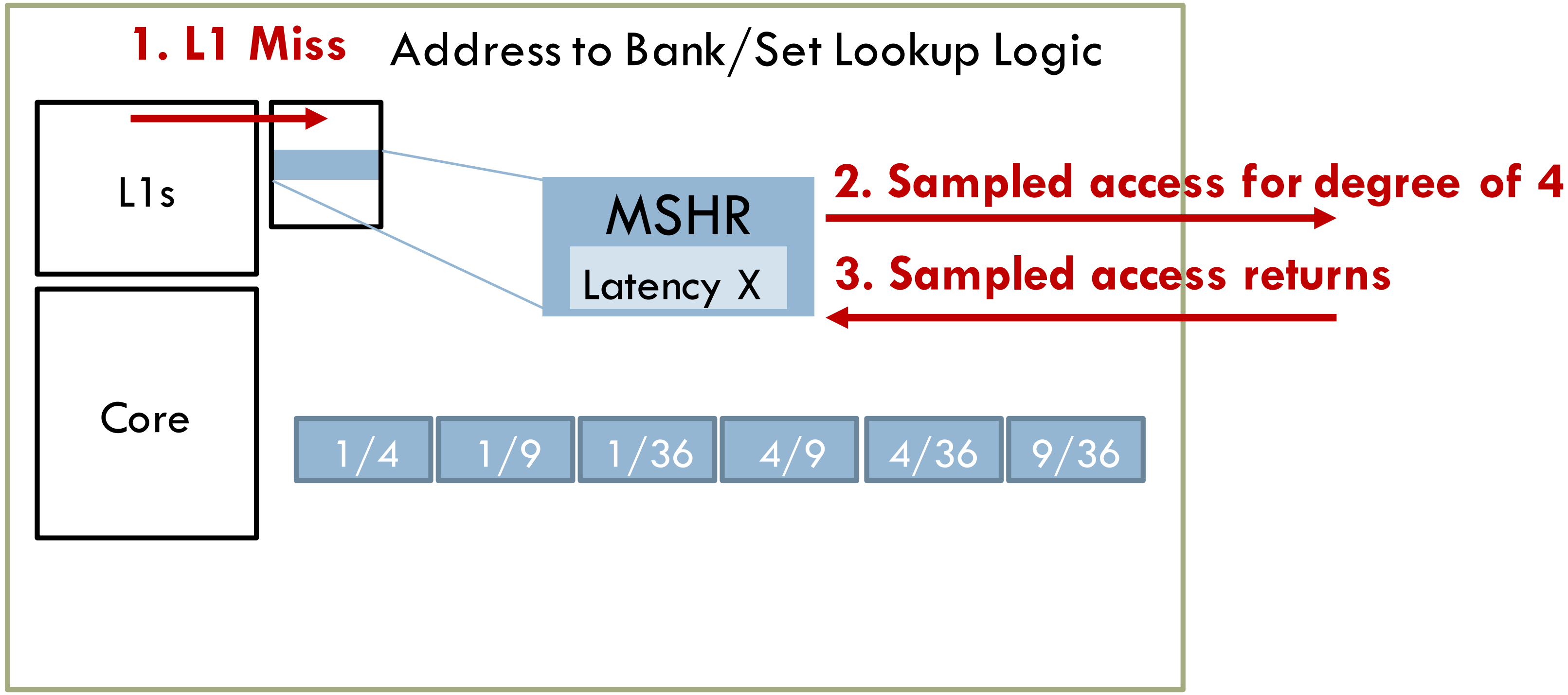

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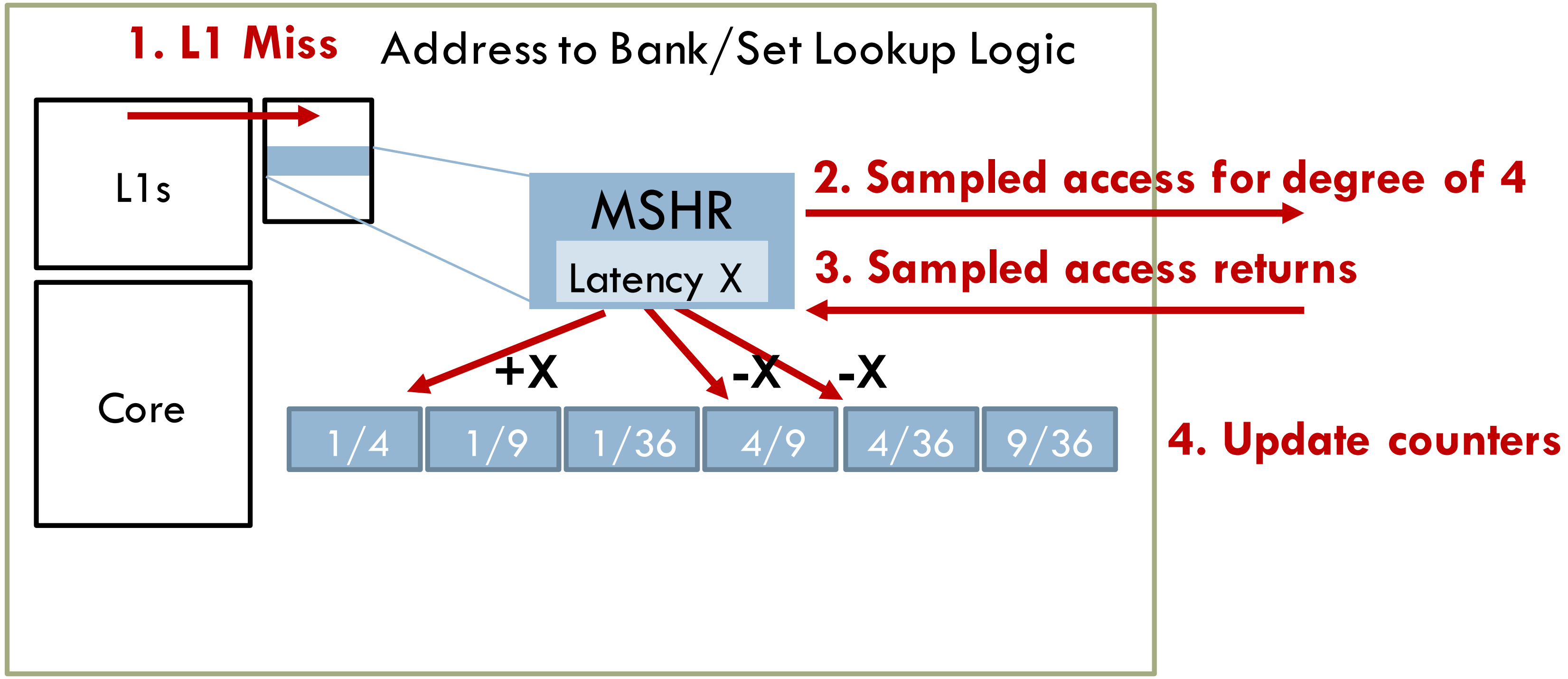

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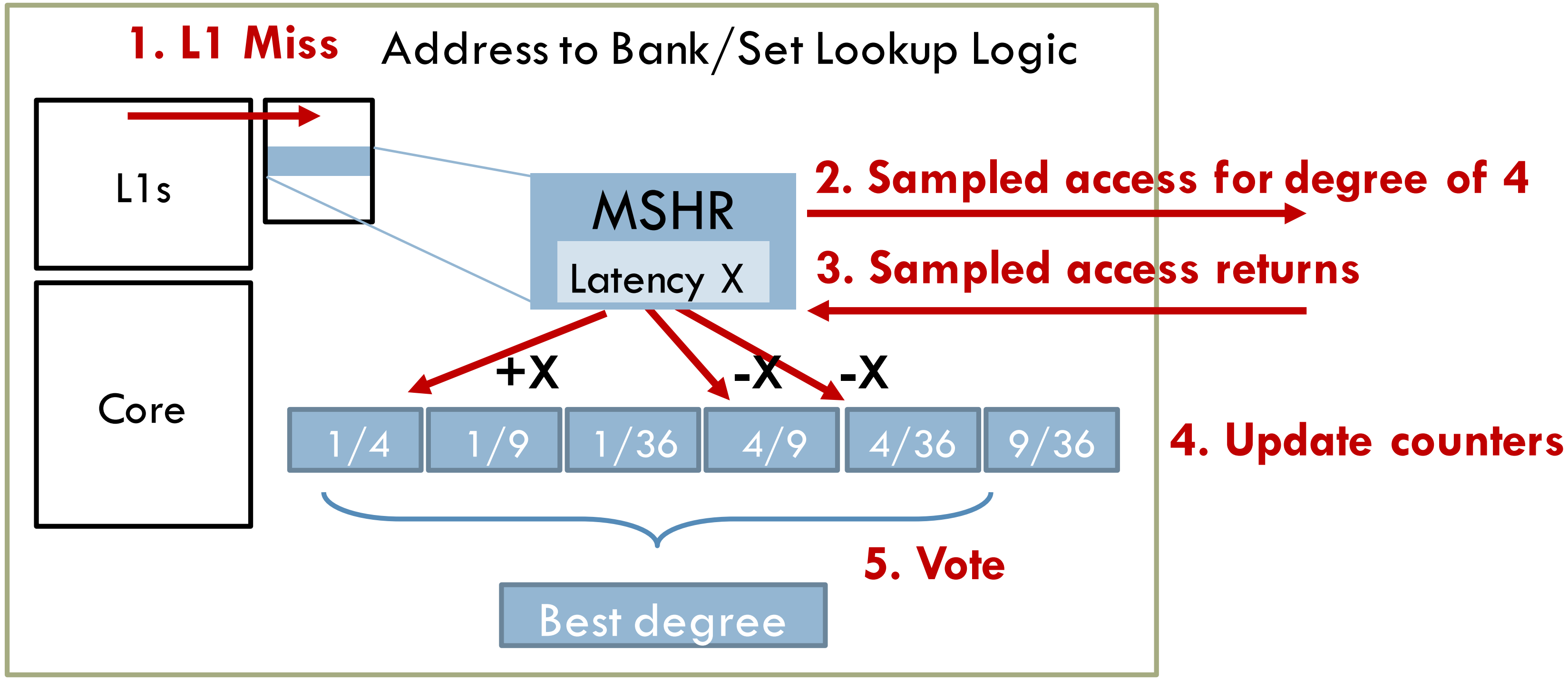

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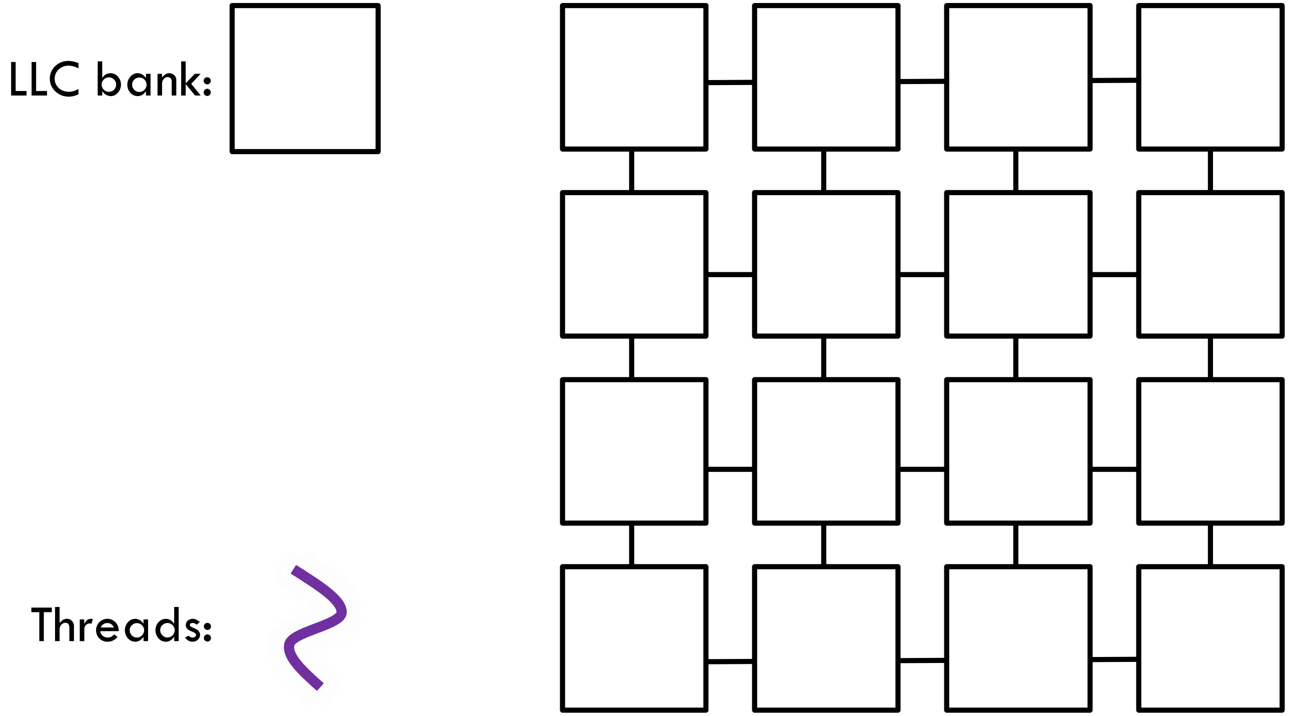

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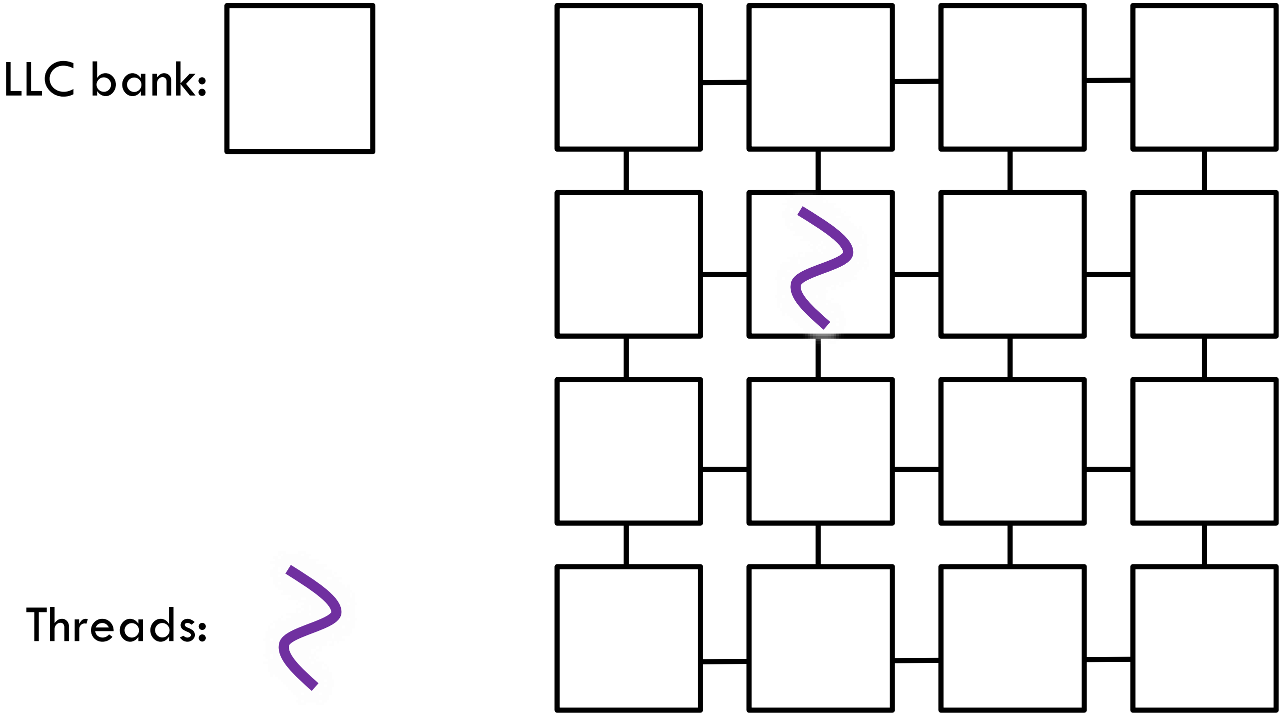

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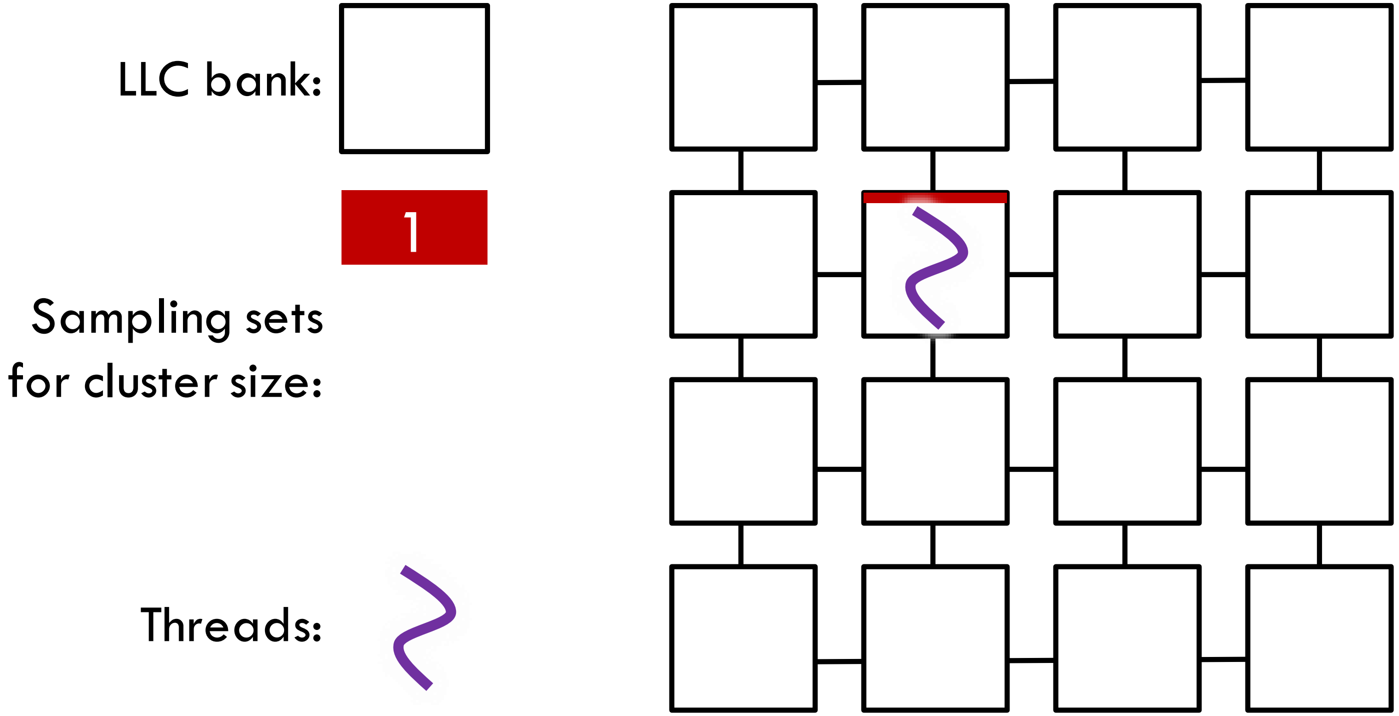

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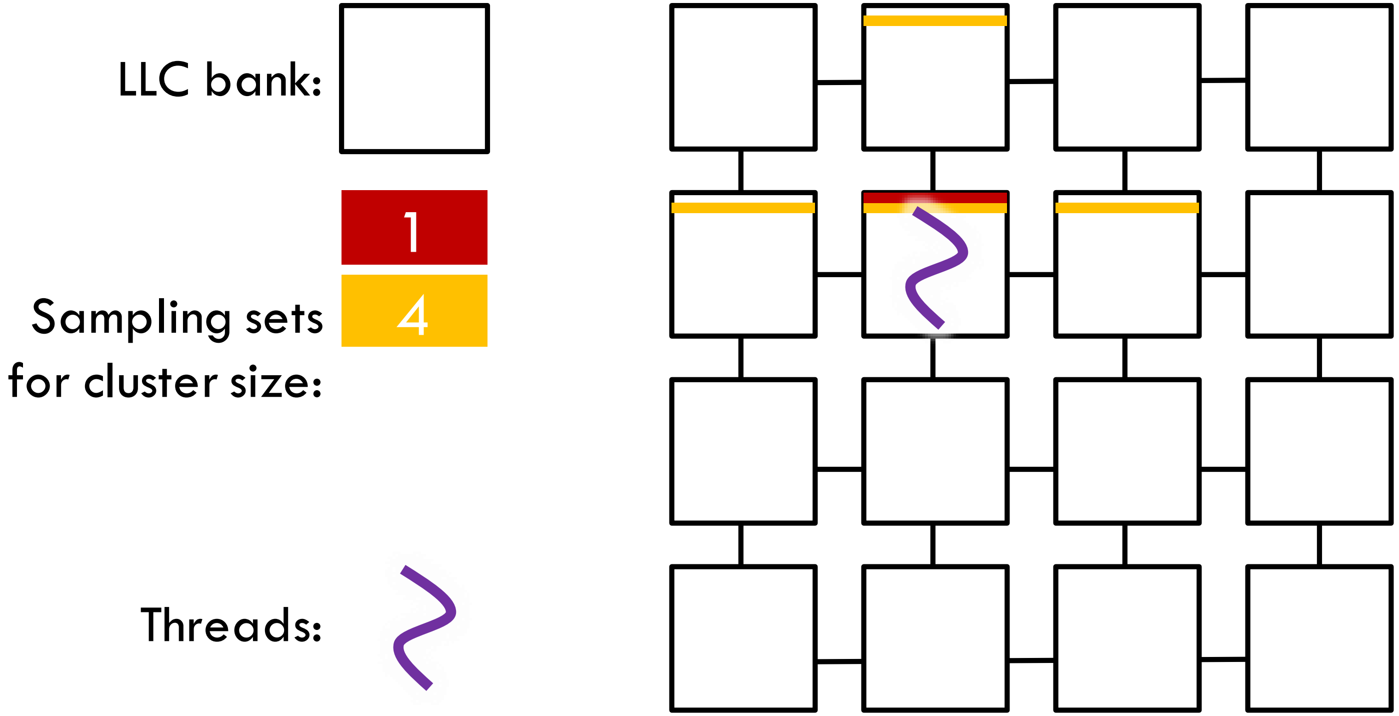

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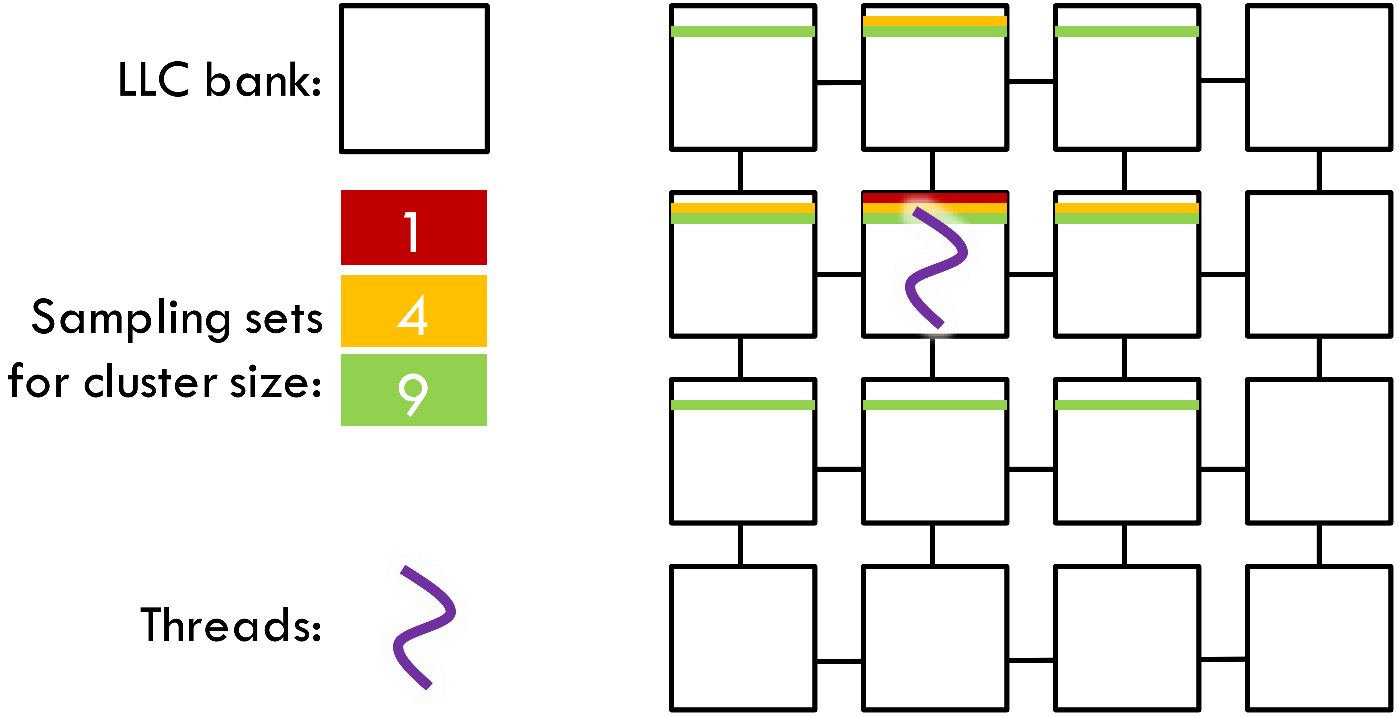

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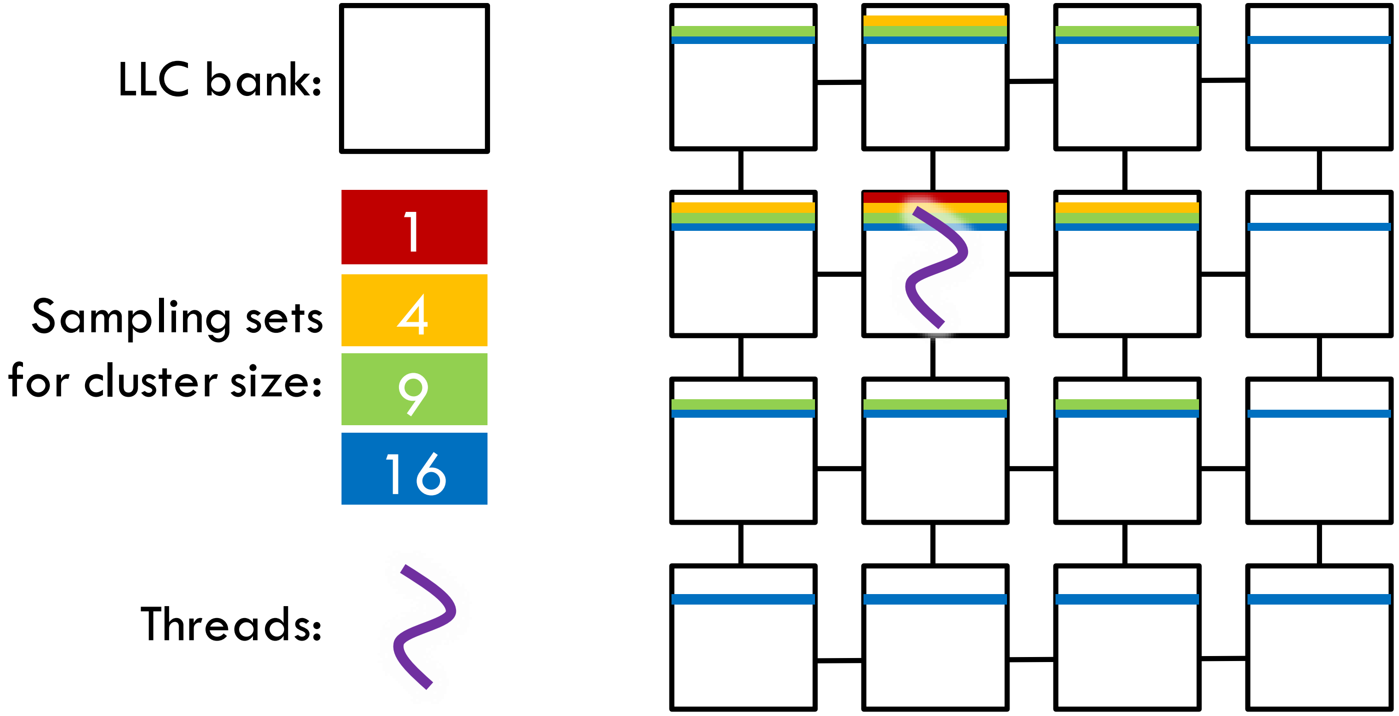

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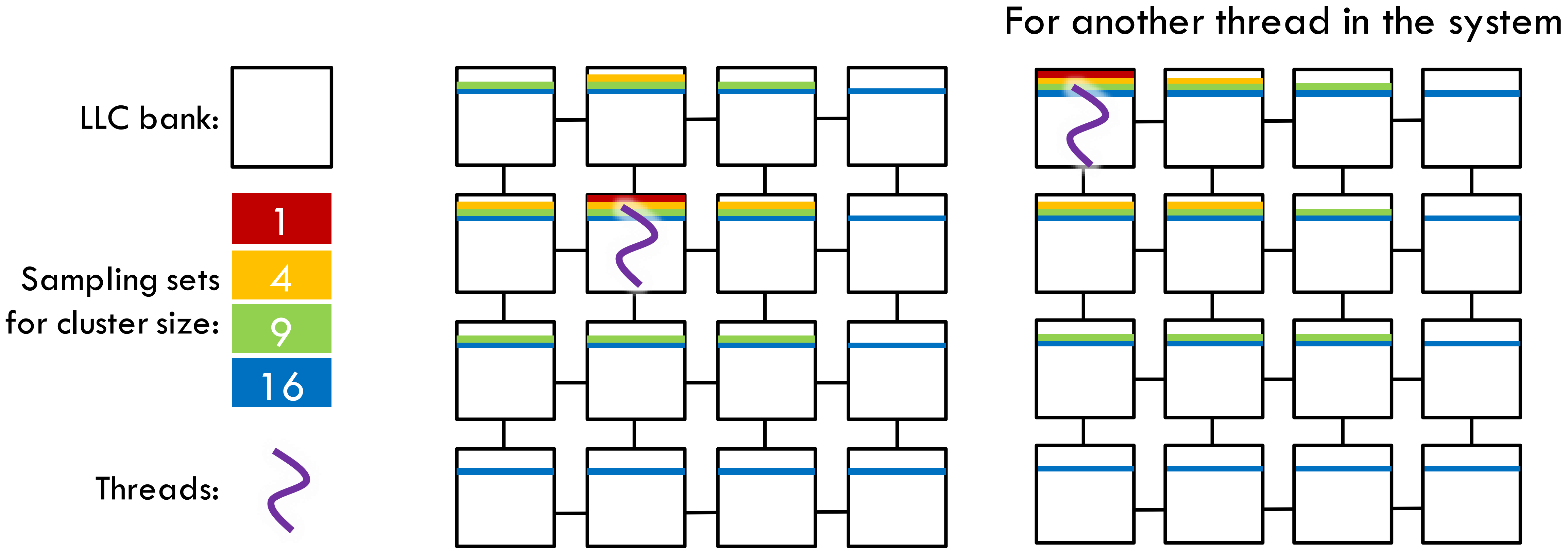

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- Uncoordinated decisions work poorly
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- Nexus-R makes **the whole process agree on the best replication degree** by using per-process total latency for each degree
  - The OS reads latency counters periodically and sets the best degree for a process

Nexus-R adds small overheads over R-NUCA

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- Overheads of applying Nexus to R-NUCA:
  - **1.5%** of the LLC used for set-sampling
  - **~100 bits** per core for hardware counters
  - **10s of instructions** per context switch for the OS support

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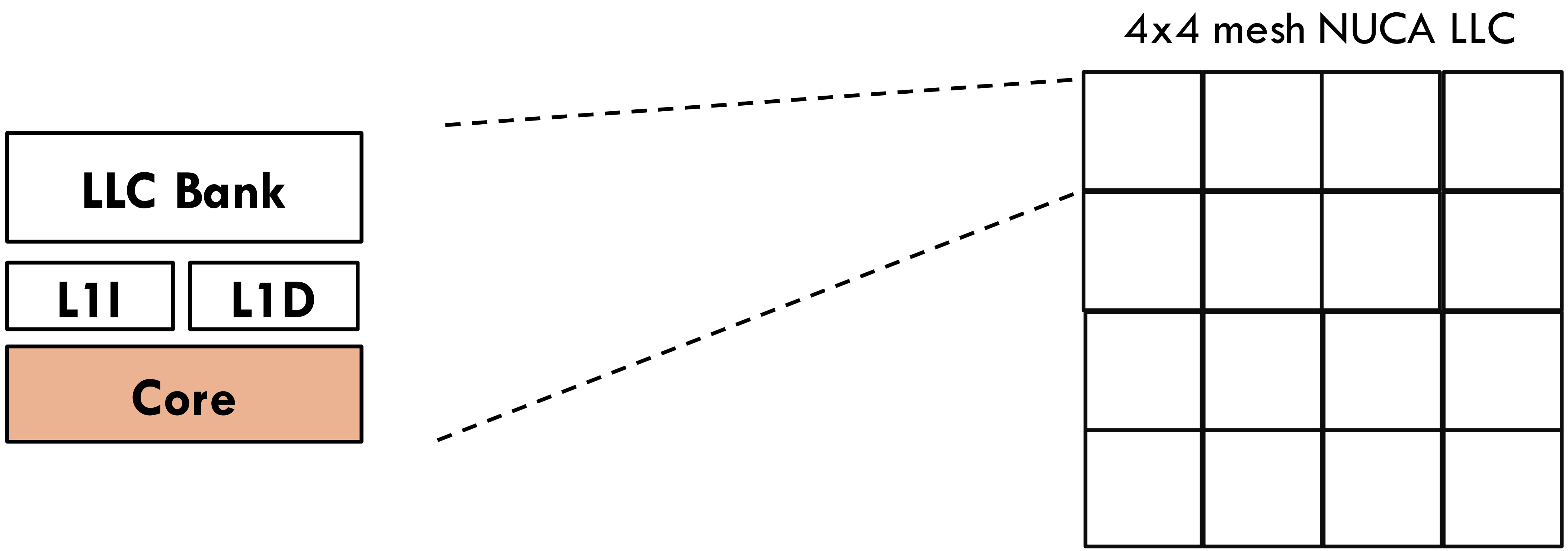
- Jigsaw groups partitions from different banks to create ***virtual caches (VCs)***



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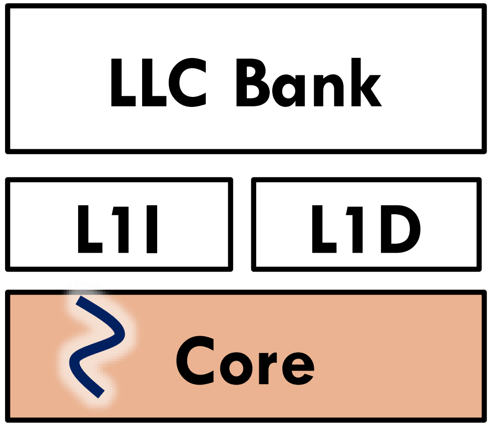

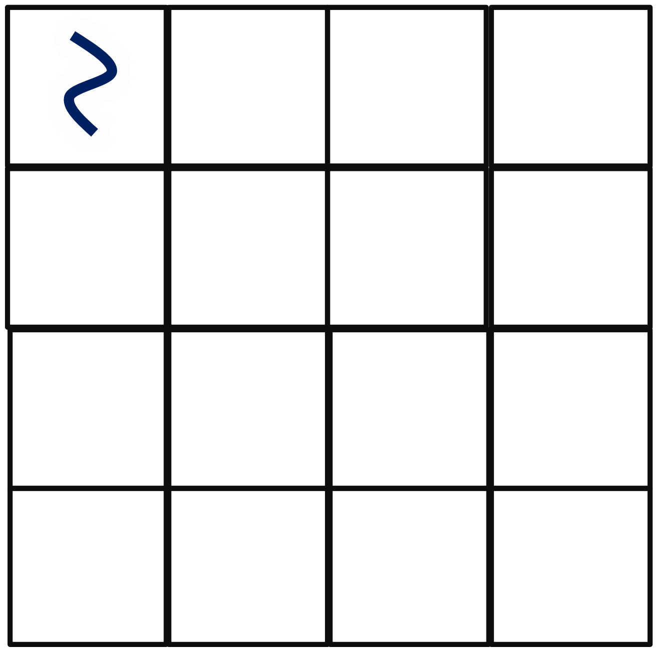

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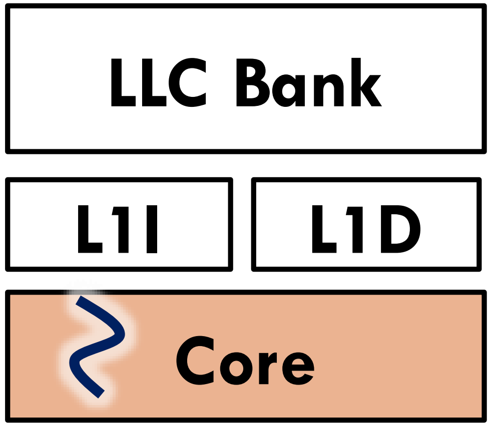
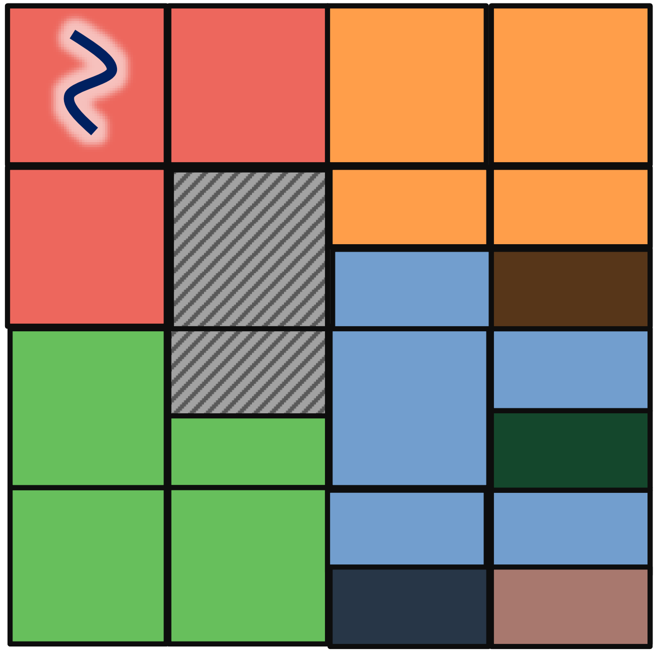
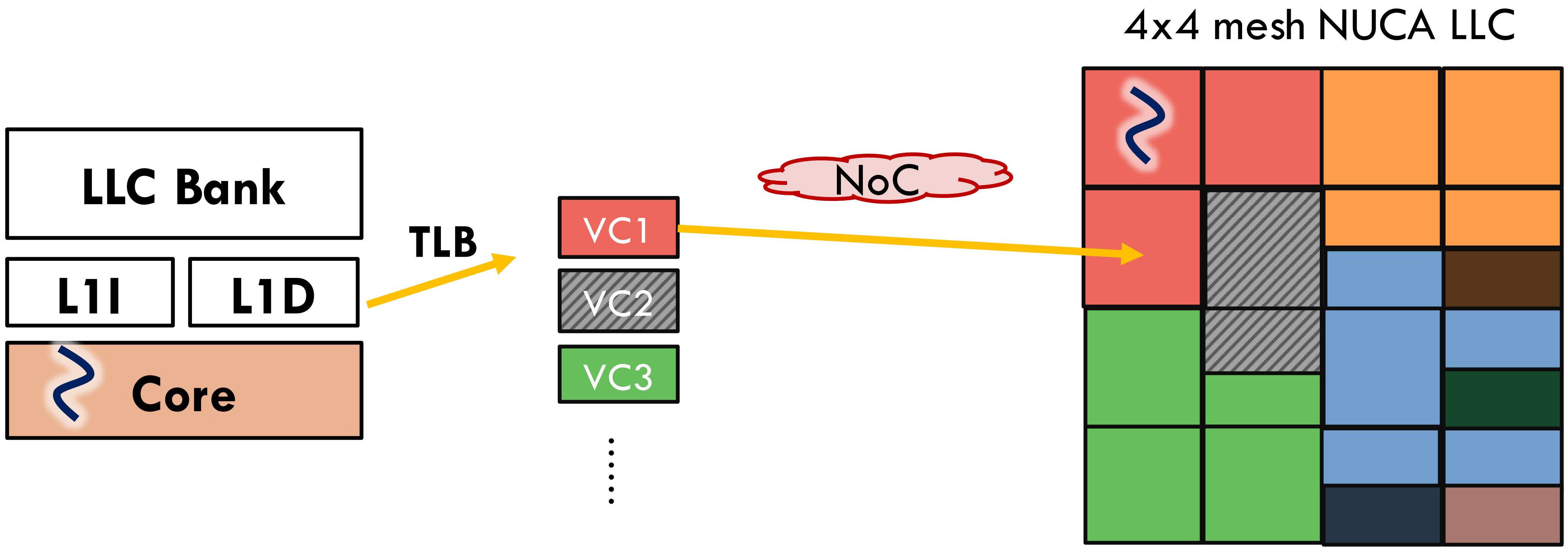


4x4 mesh NUCA LLC



Nexus-J: Applying Nexus to Jigsaw

- Jigsaw groups partitions from different banks to create ***virtual caches (VCs)***



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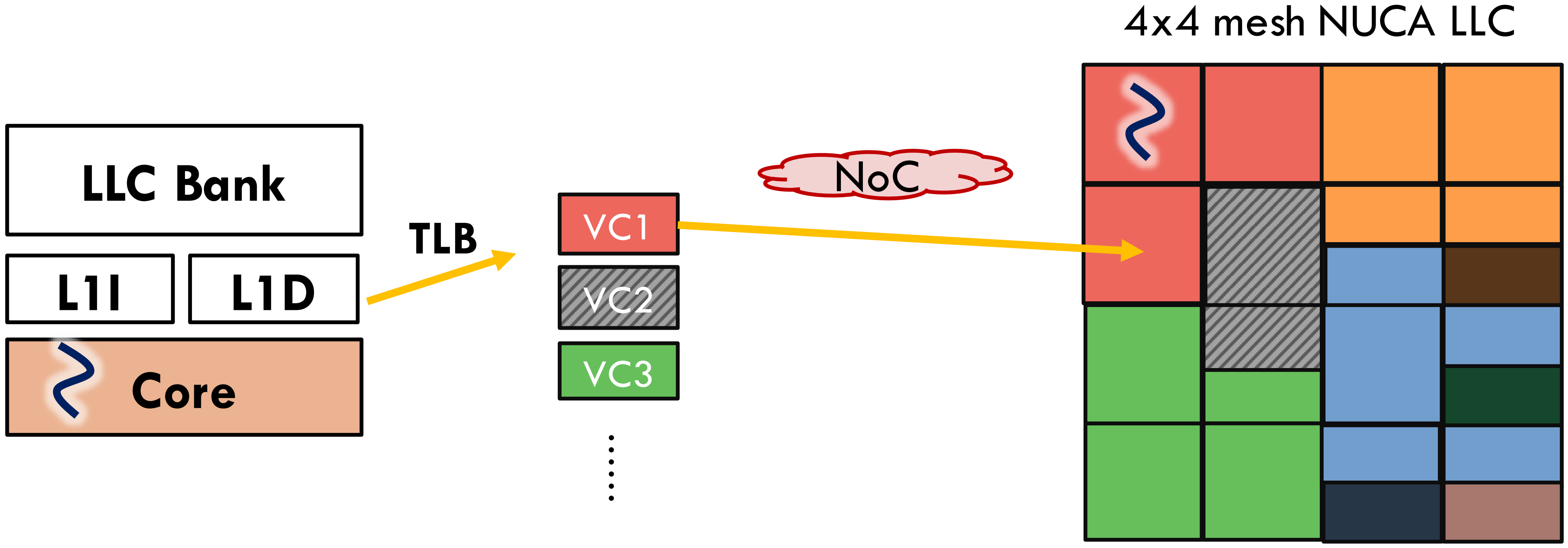

Jigsaw manages capacity among applications and data types, outperforming many D-NUCA techniques

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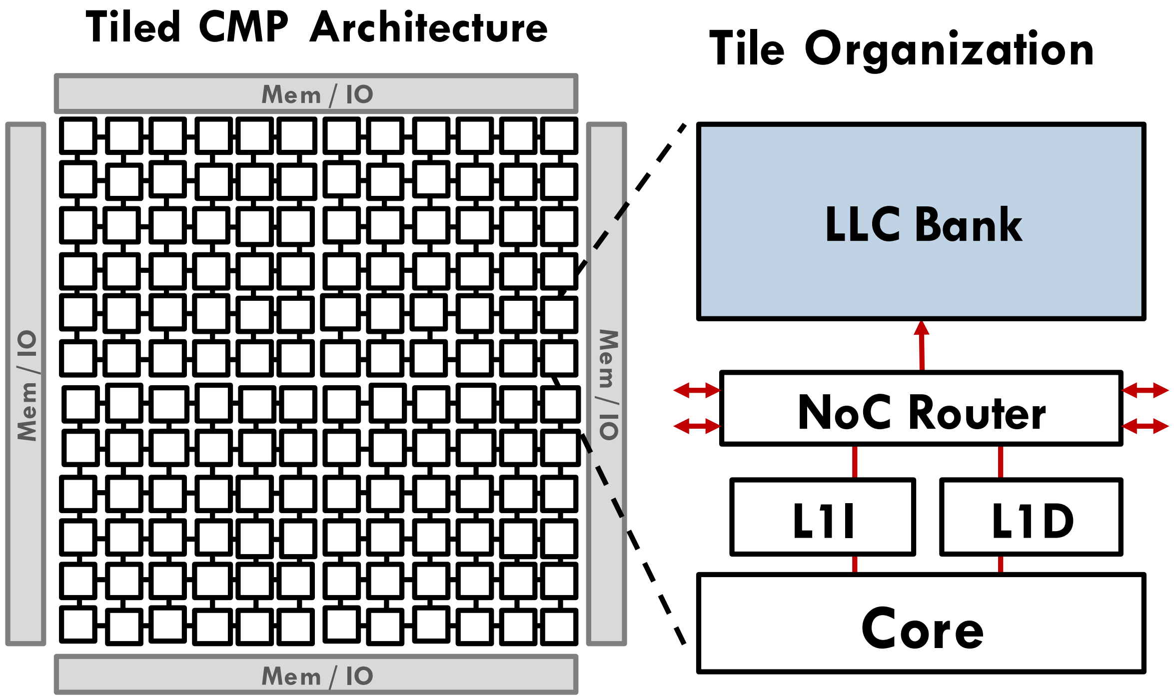
- See the paper for implementation details

Evaluation

- Modeled system
  - 144 Silvermont-like OOO cores
  - 12x12 mesh
  - 32KB L1I/D caches
  - 72MB LLC (0.5MB per core)



- Multithreaded workloads
  - Scientific workloads: SPECOMP2012, PARSEC, SPLASH2, BioParallel
  - Server workloads: TailBench [Kasture, IISWC'16]
  - With various input sizes

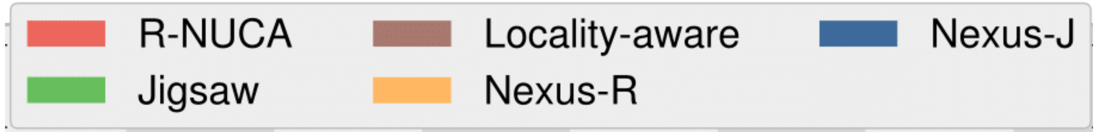
Evaluation

- Compared 6 schemes

S-NUCA	No replication (baseline).
R-NUCA	Replicate instructions at a fixed degree.
Jigsaw	Allocate capacity across processes. No replication.
Locality-aware replication [Kurian, HPCA'14]	State-of-the-art directory-based D-NUCA. Selectively replicate cache lines in local bank.
Nexus-R	**Nexus on R-NUCA.**
Nexus-J	**Nexus on Jigsaw.**

Nexus outperforms prior selective replication techniques

- Single-program workloads running with 144 threads



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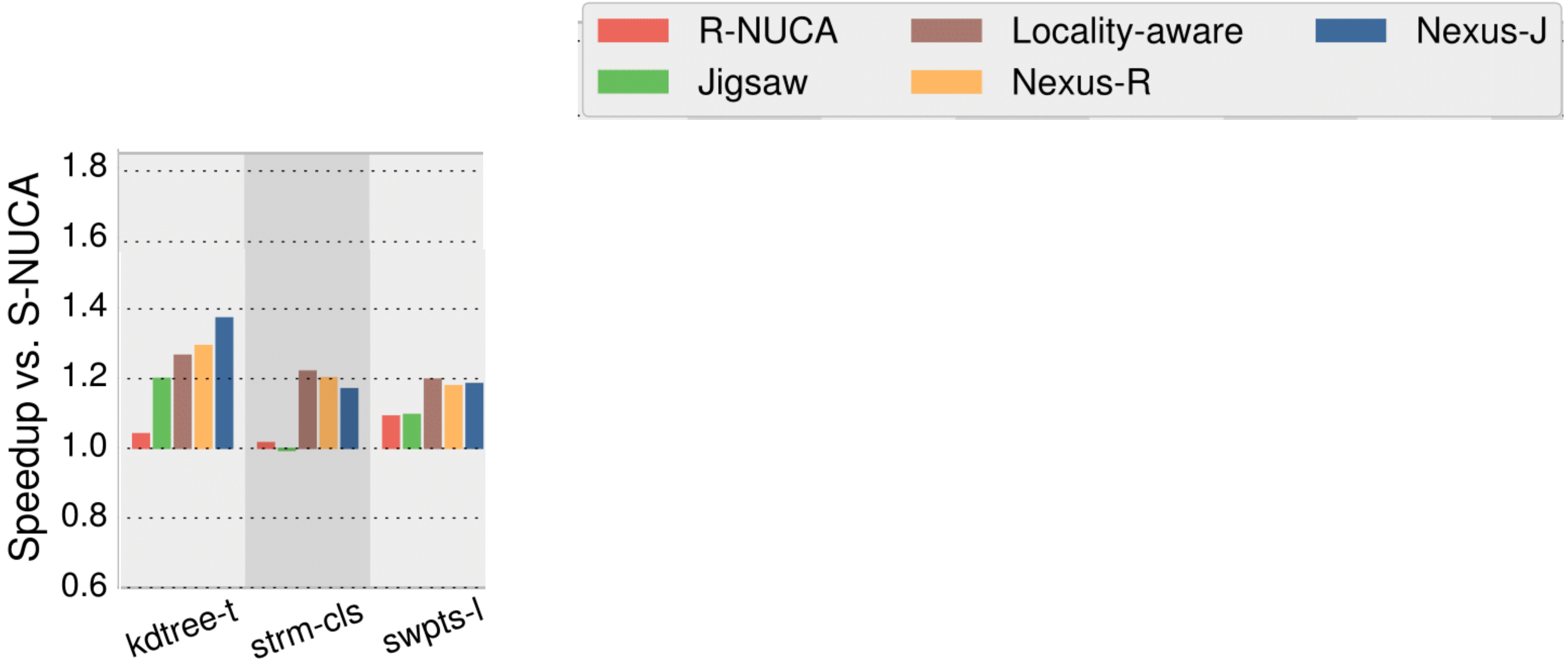

Workloads with small read-only footprint → Nexus **matches** prior work

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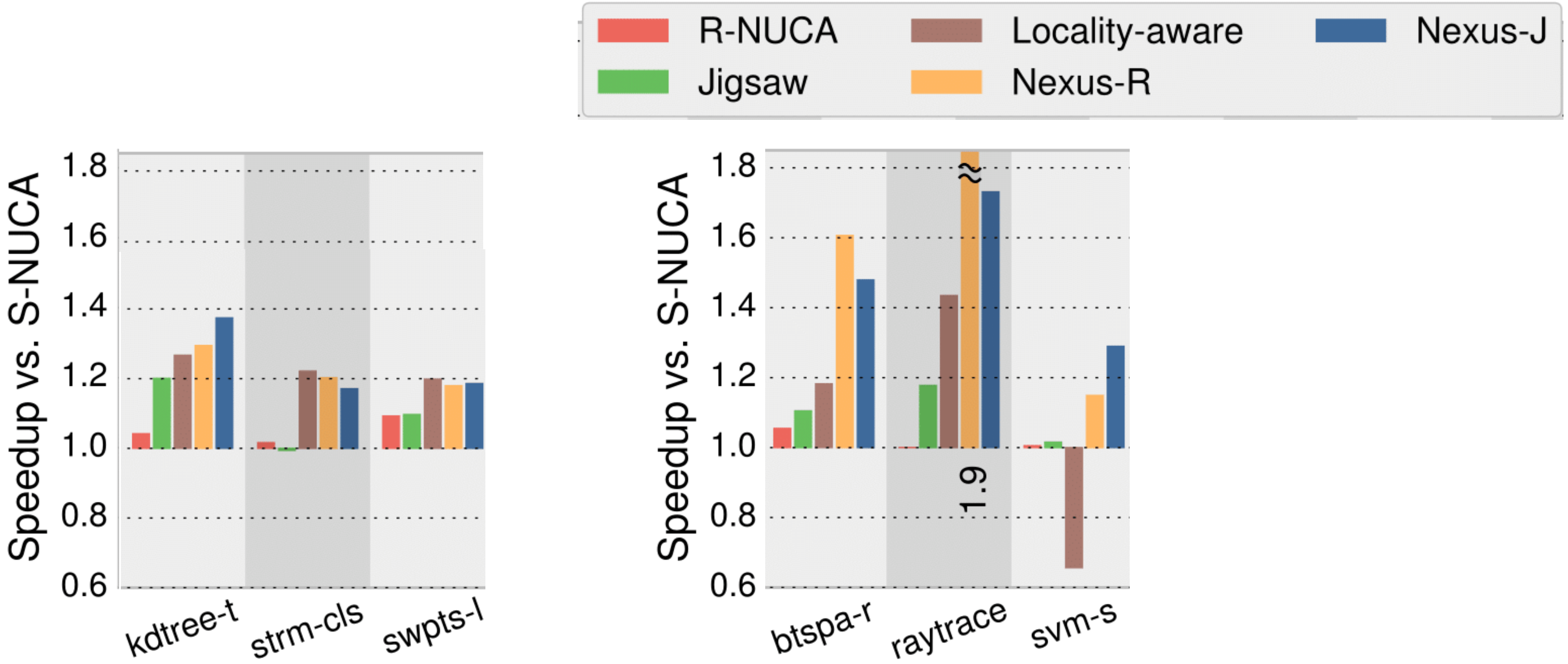

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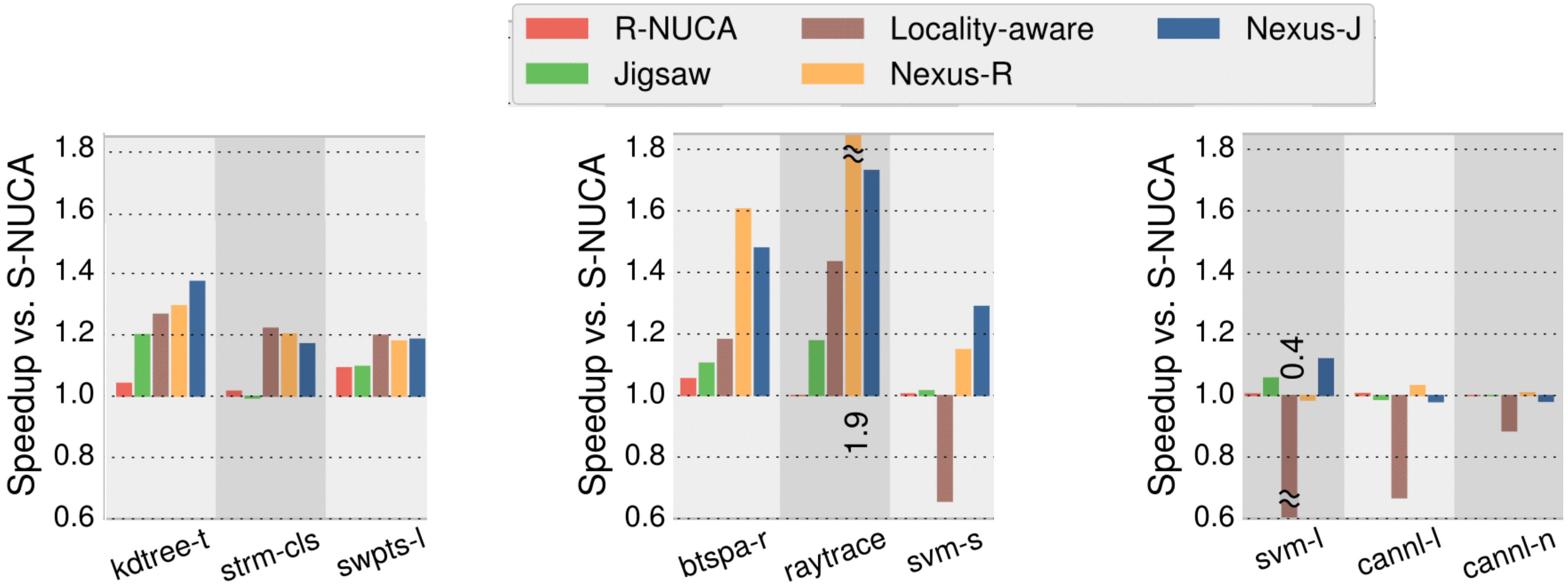

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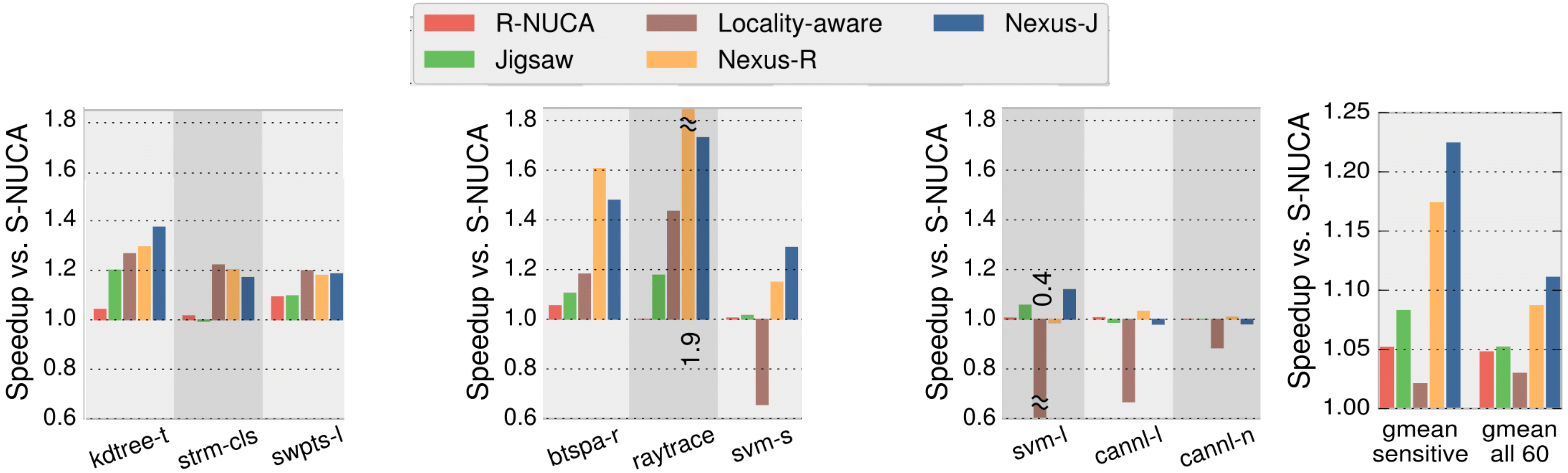

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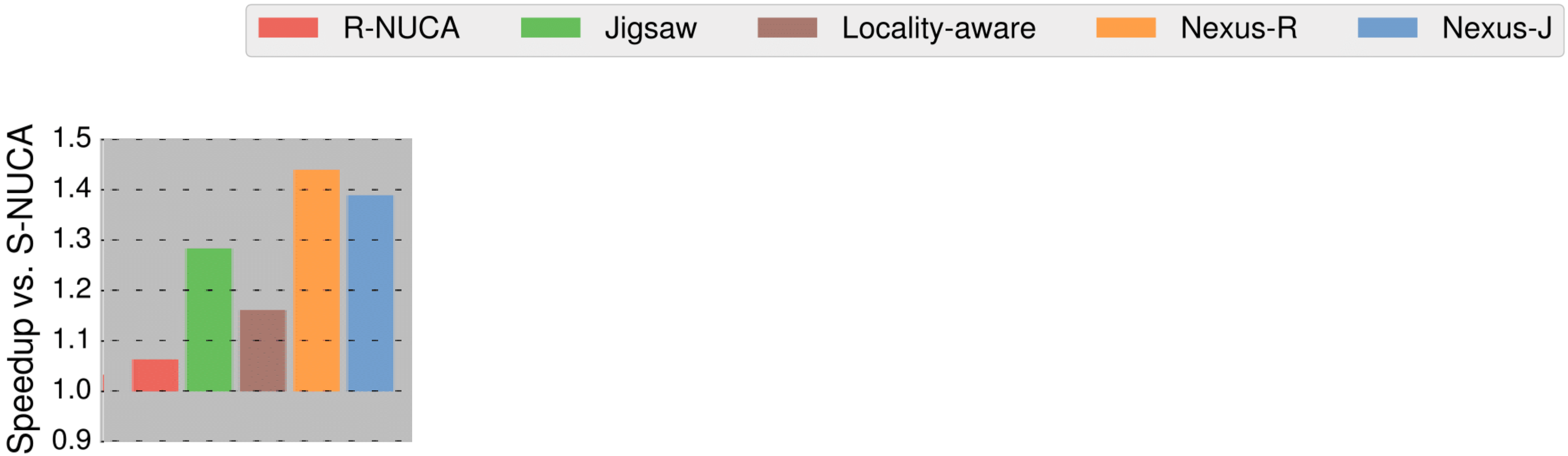

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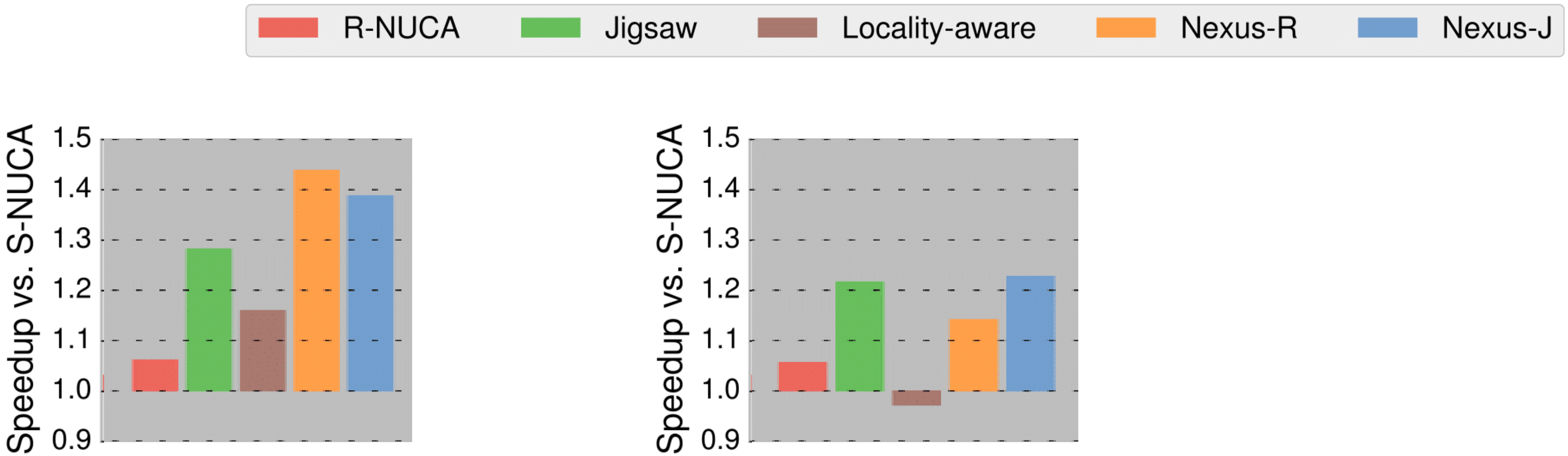

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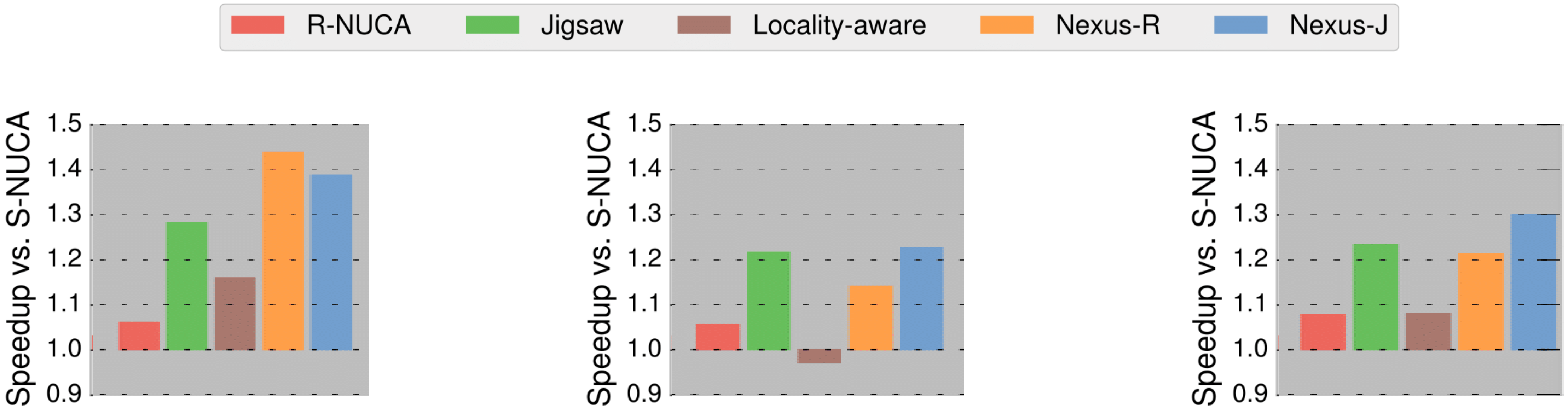

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Sensitive to both → **Nexus-J** performs the best

See paper for more results

- Performance of 60 apps between Nexus-R and Locality-aware replication
- Dynamic replication degree vs. static degrees
- Result of 20 Multi-program workloads
- Sensitivity study to
  - System sizes
  - Different cache hierarchies
- Dynamic data reclassification

Conclusion

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Thanks! Questions?

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