PIM-tree: A Skew-resistant Index for Processing-in-Memory

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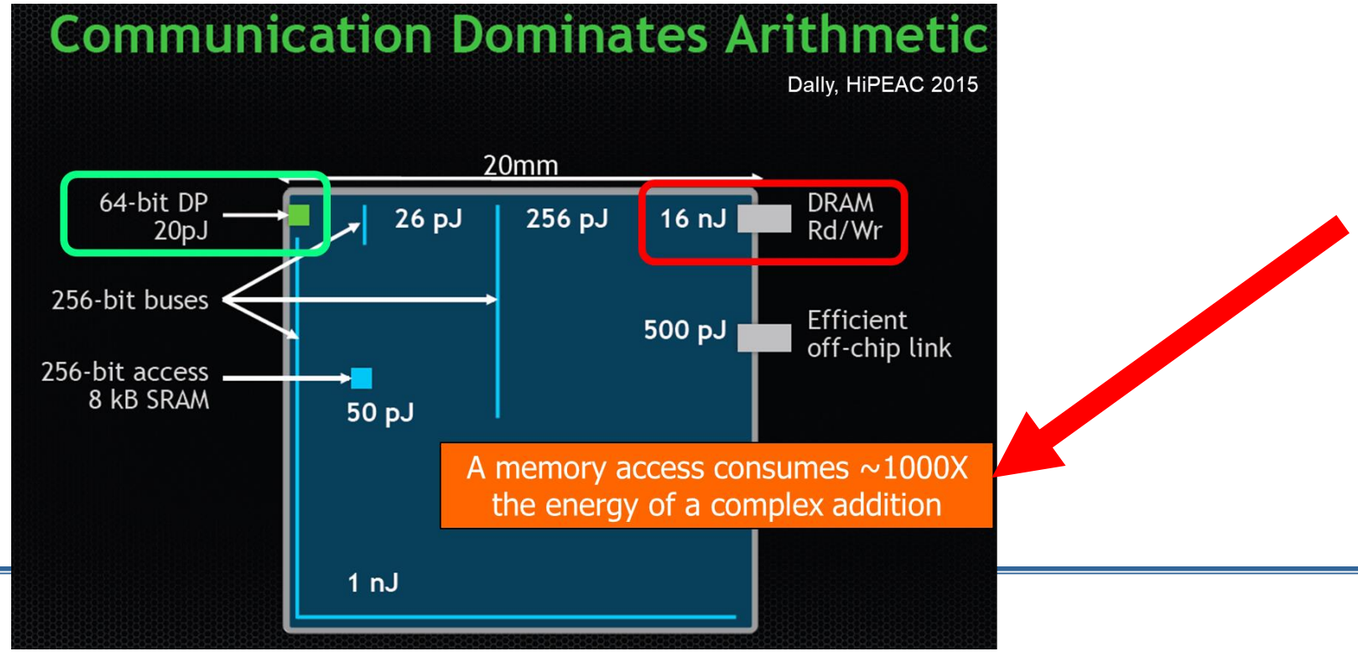
CMU

The Memory Wall Problem

- Memory Wall
  - Widening gap between the processor performance and memory access speed (memory bandwidth/latency).
  - High power consumption of data movement.
- Data movement becomes the key bottleneck.



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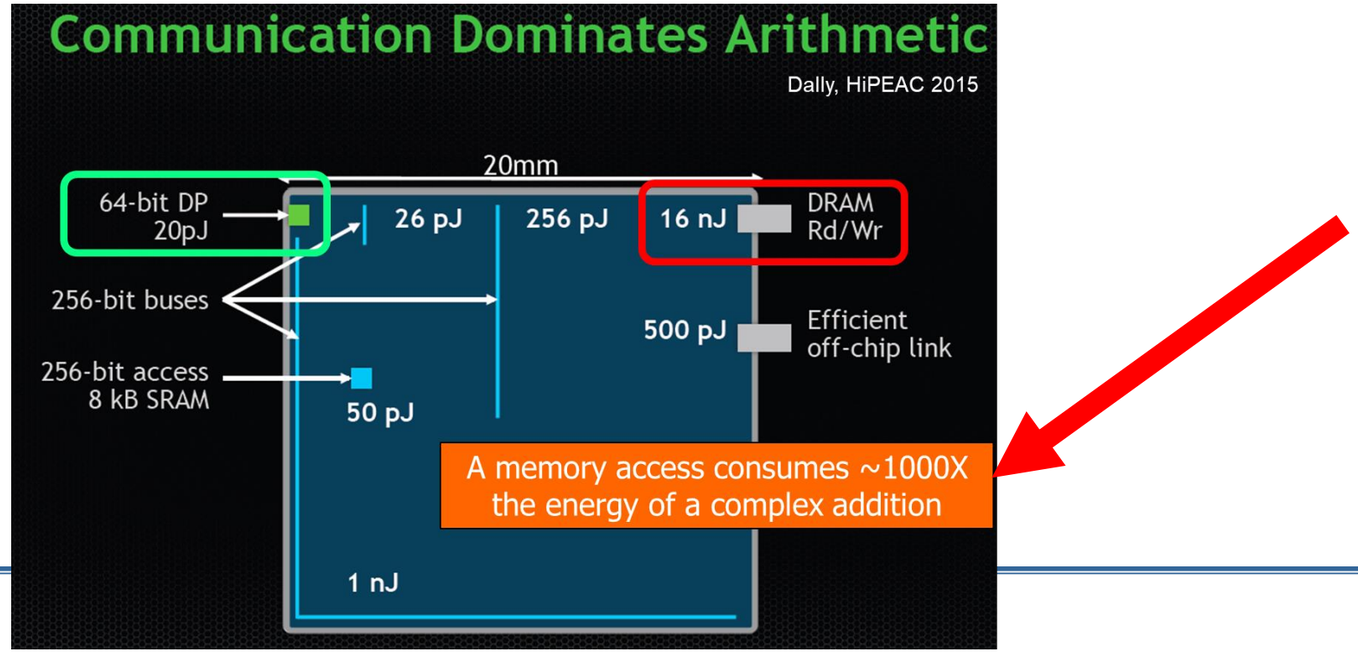

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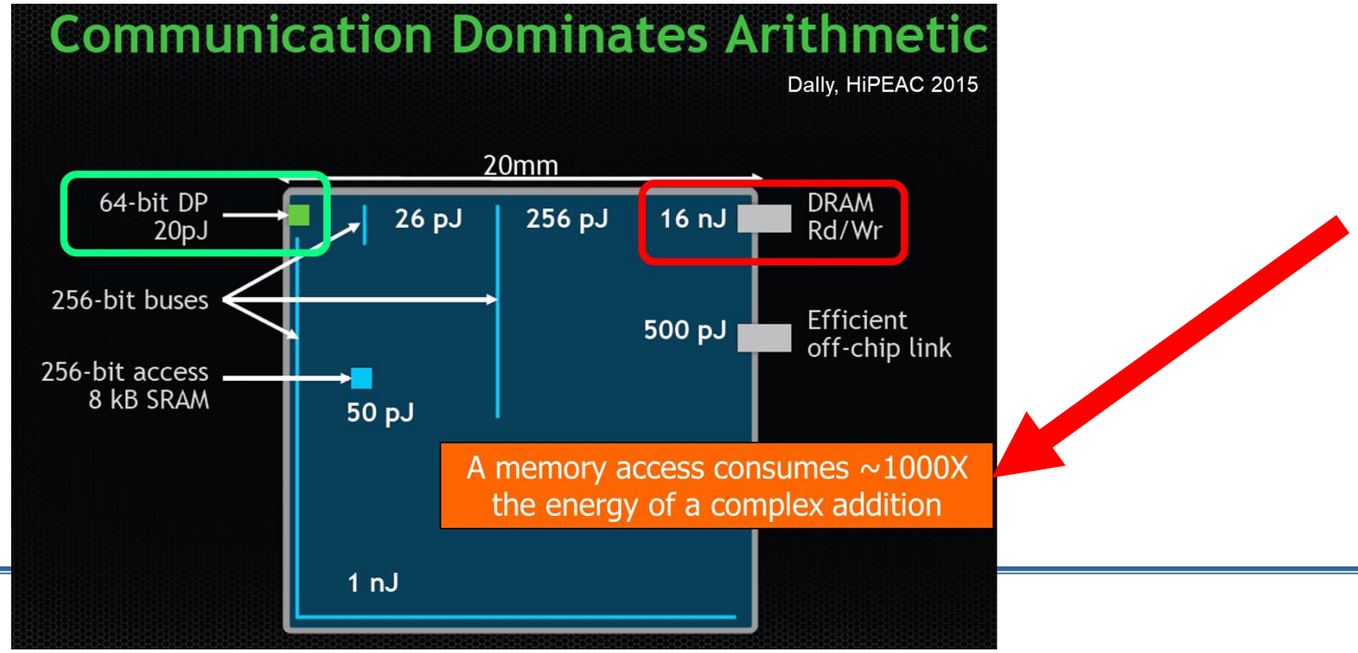

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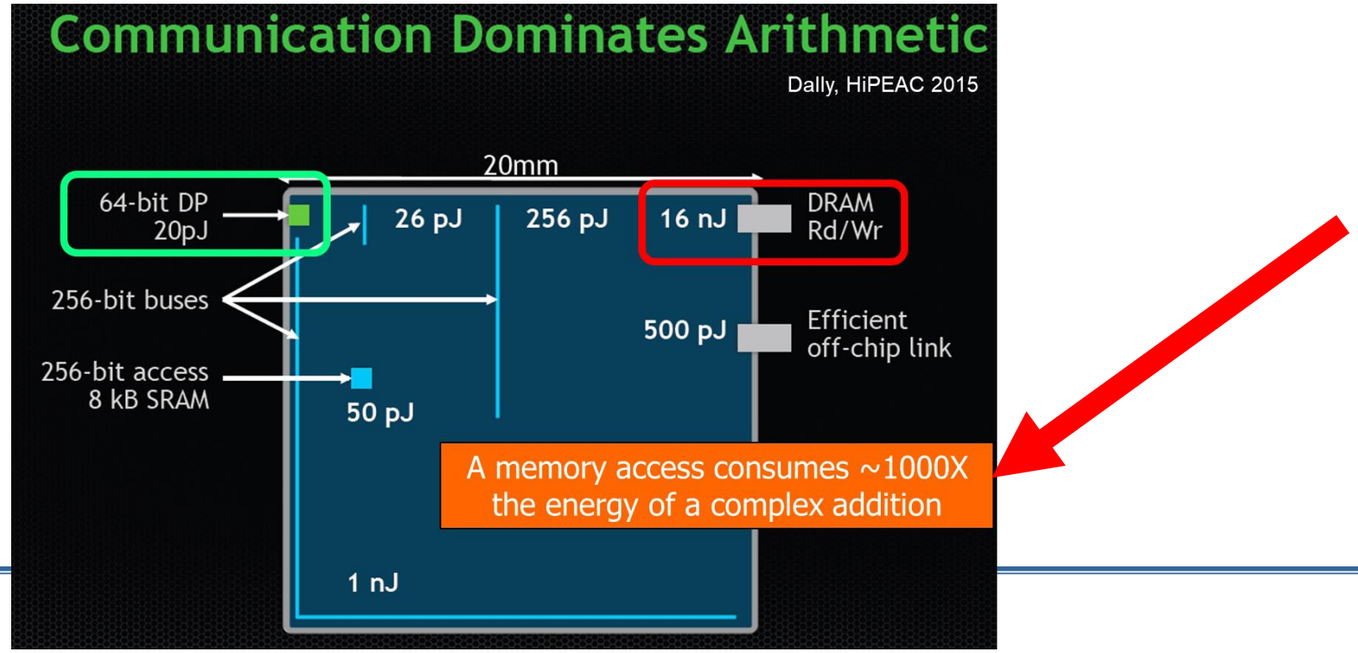
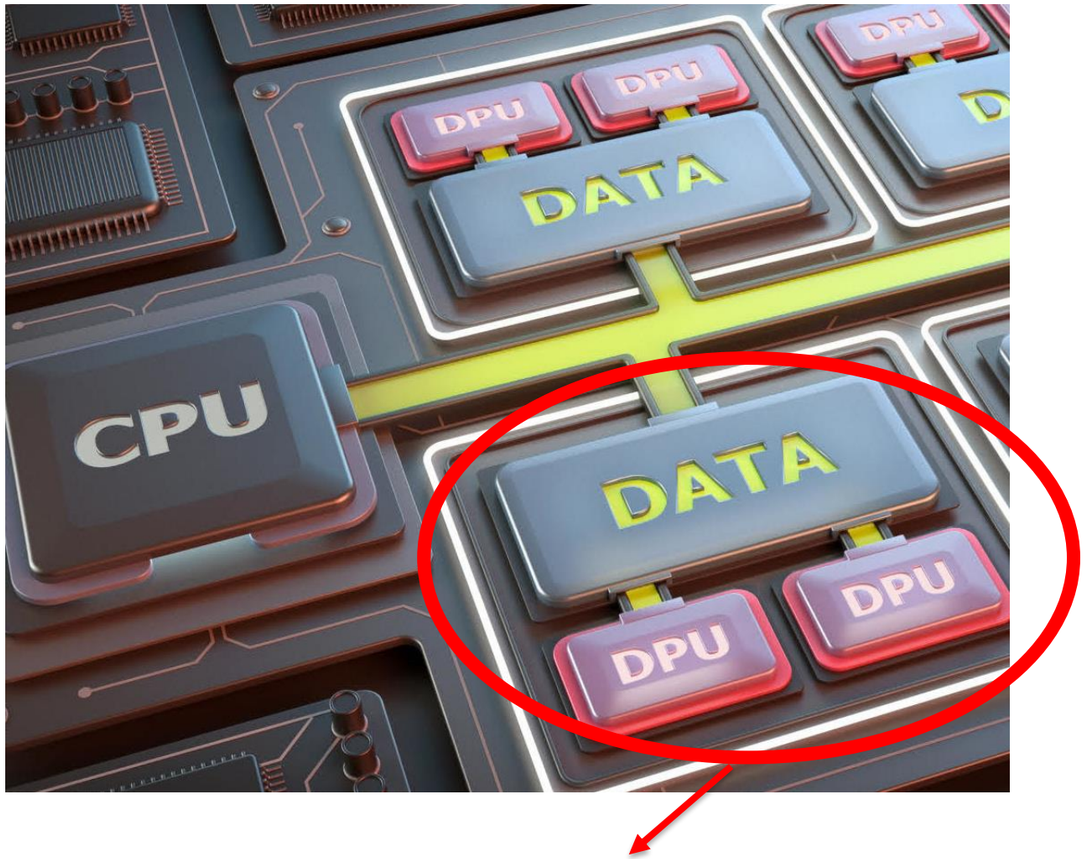


Processing-in-Memory (PIM)

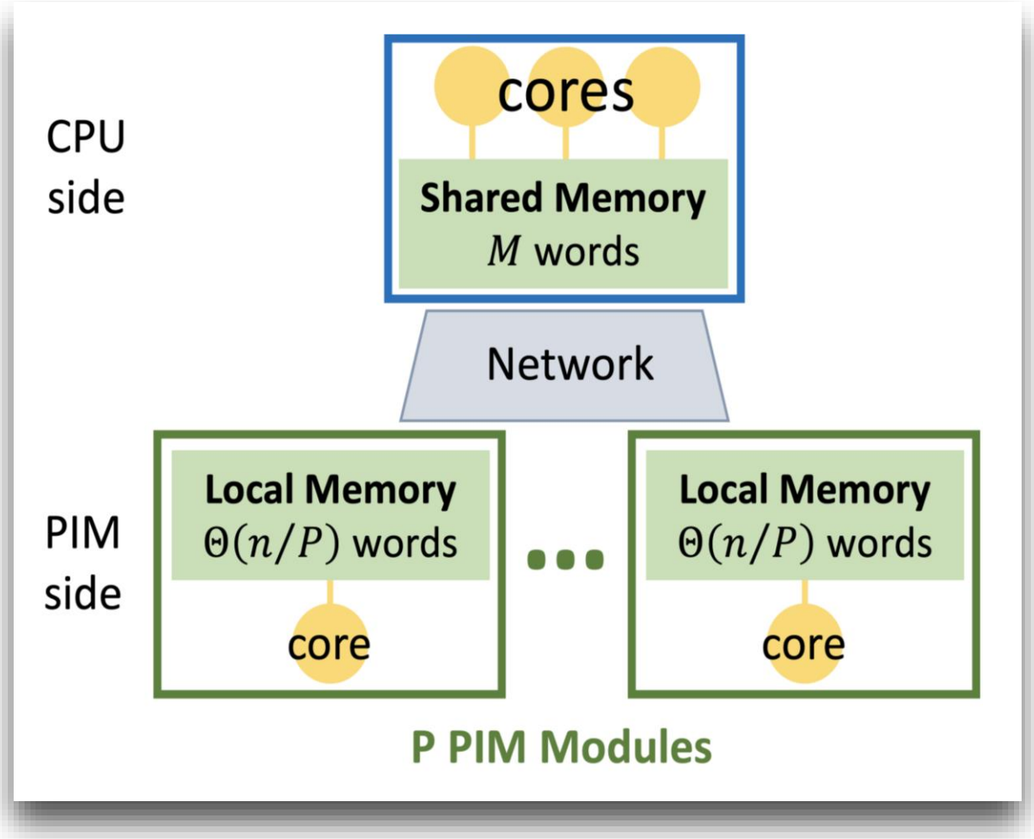
- Processing-in-memory enables computation to be pushed to memory
  - Appears in 1970s
  - Advance in memory tech.
  - Core(s) in each memory module



PIM module:
Data Processing Unit (PIM core)
& the local memory it can visit

The Processing-in-Memory Model*

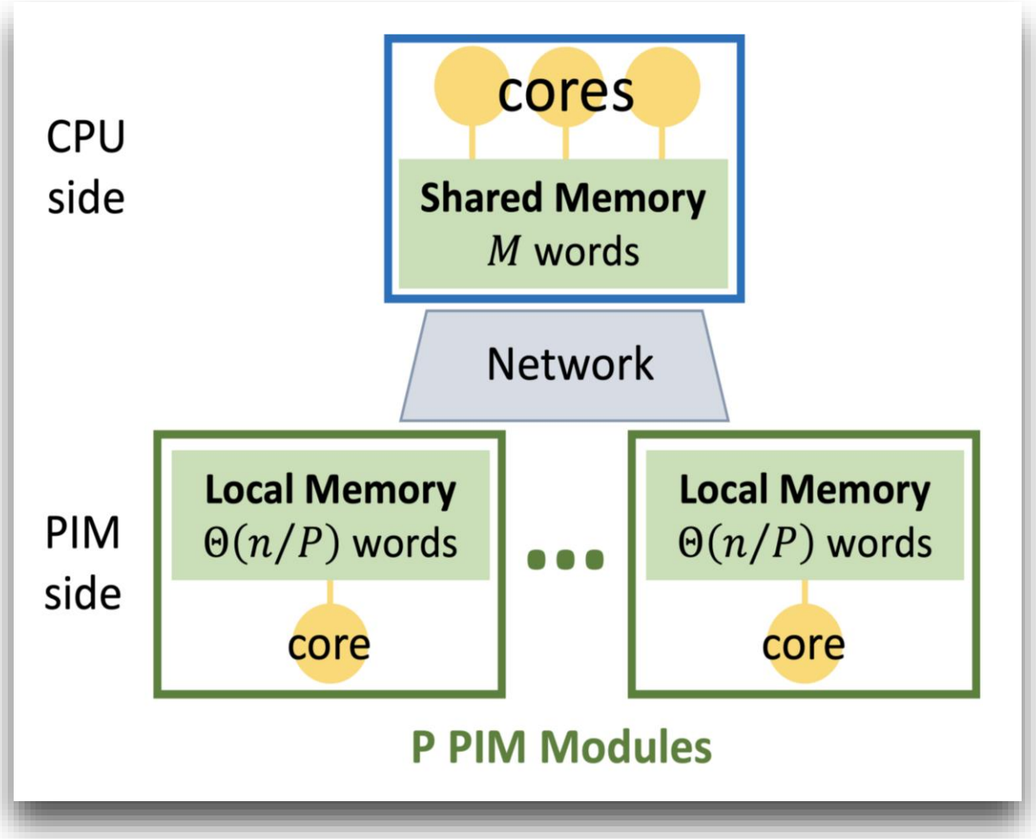
- One multicore CPU side
  - With a shared cache (LLC) of size M words
- P PIM modules in total
- Each PIM module
  - One PIM core that can only visit local memory & communicate with CPU through network
  - Local memory sized $\Theta(n/P)$** words



*** Kang, et al. The Processing-In-Memory Model. SPAA'21.**
**** n is the problem size / input data size.**

The Processing-in-Memory Model

- BSP style execution
  - Synchronous rounds
- Metrics
  - CPU work & span
  - PIM time: Maximum work on any PIM processor
  - IO time: Maximum number of word-sized messages from/to any PIM module



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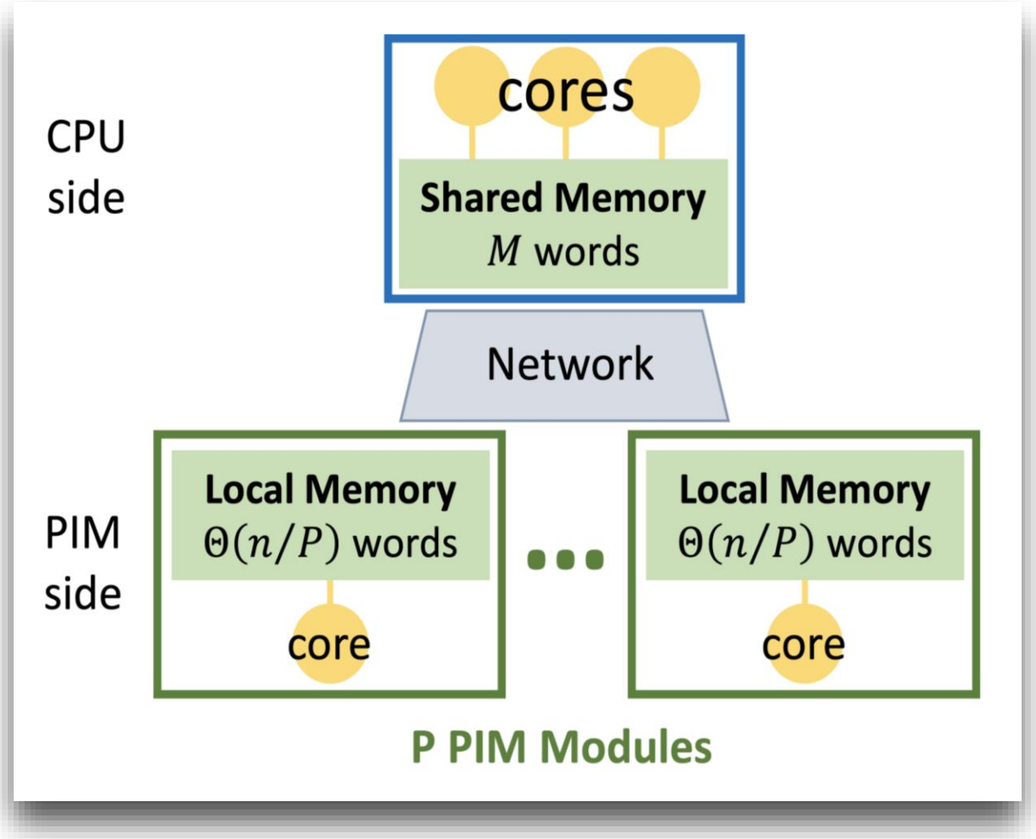
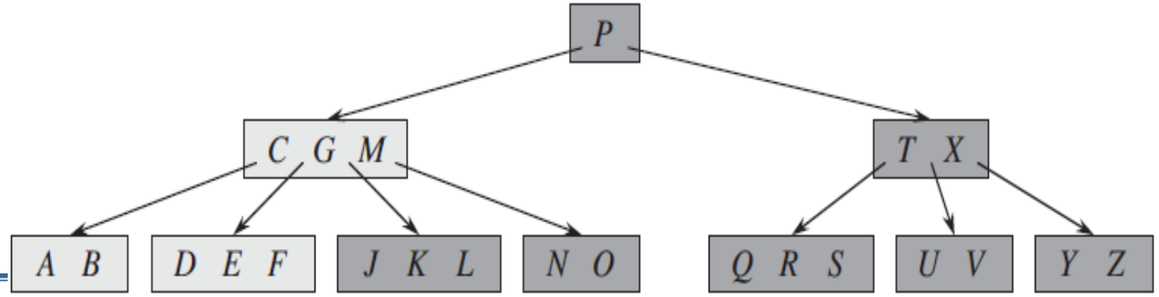


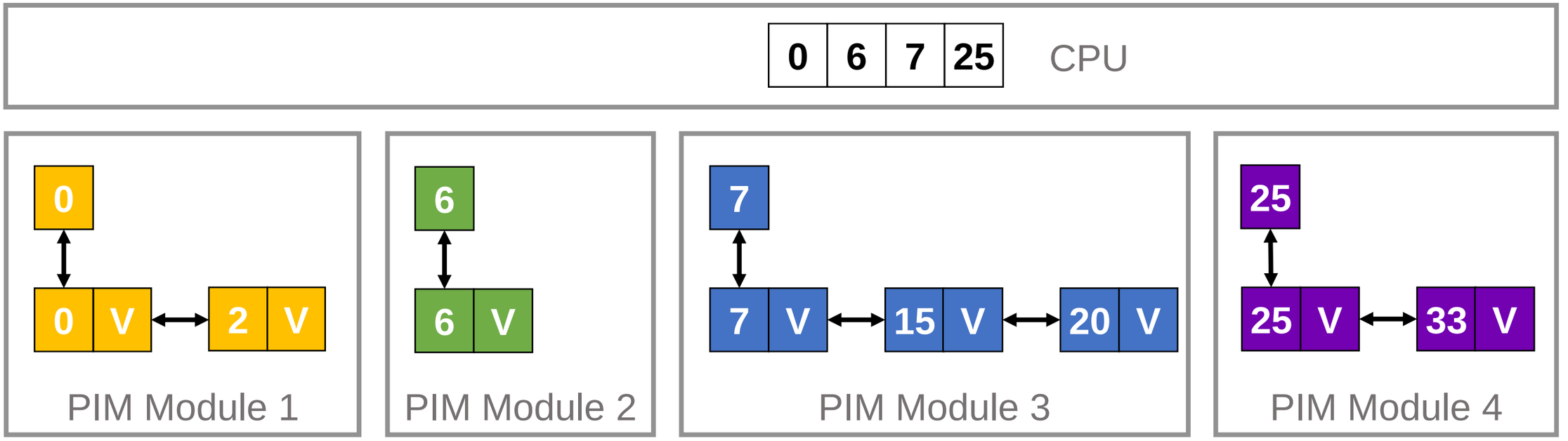
Pointer-Chasing Index

- Core block for in-memory storages.
  - Victim of its serial random memory access pattern (pointer-chase)
- Store key-value paired data
- Support operations:
  - Get(key)
  - Insert(key, value) & Delete(key)
  - Predecessor/Successor(key) & Range(Lkey, Rkey)
- Batch Parallel Execution
- Skip list
  - B-tree?



Prior Work: PIM-based Ordered Indexes*

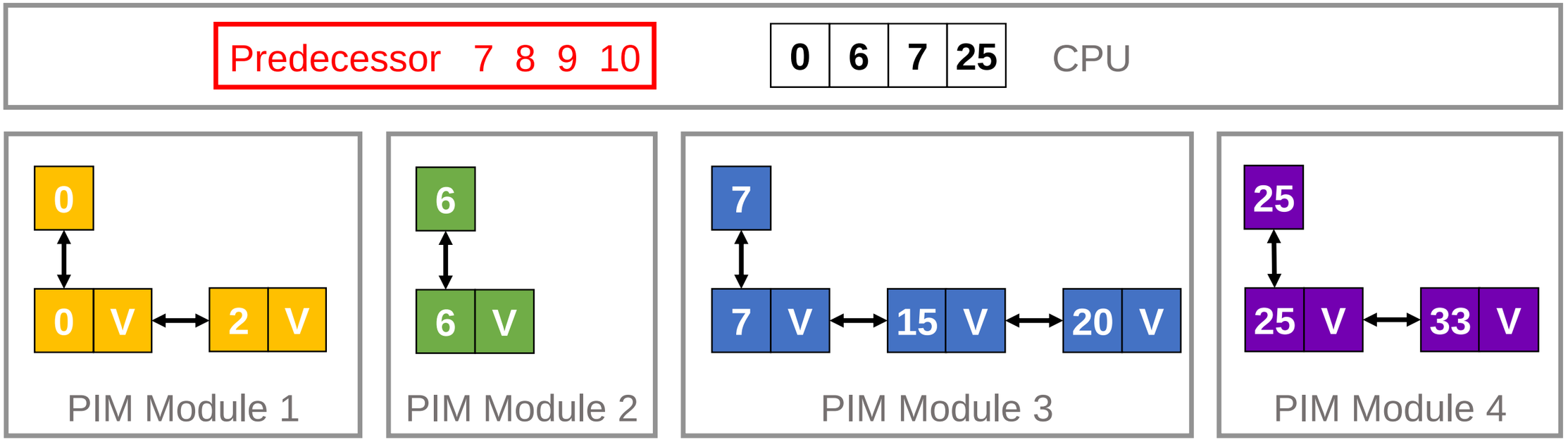
- Range-partitioning: Local skip lists for disjoint key ranges
- Pros:
  - Low data movement: Constant per point operation
  - Parallelism for keys in different ranges



*** Choe, et al. Concurrent Data Structures with Near-Data-Processing. SPAA'19.**

Drawbacks of Range Partitioning Indexes*

- Cons: Vulnerable to **skewed** operations batches
  - Query skew occur in real datasets: YCSB, …
  - Uneven distribution of keys cause **load imbalance**



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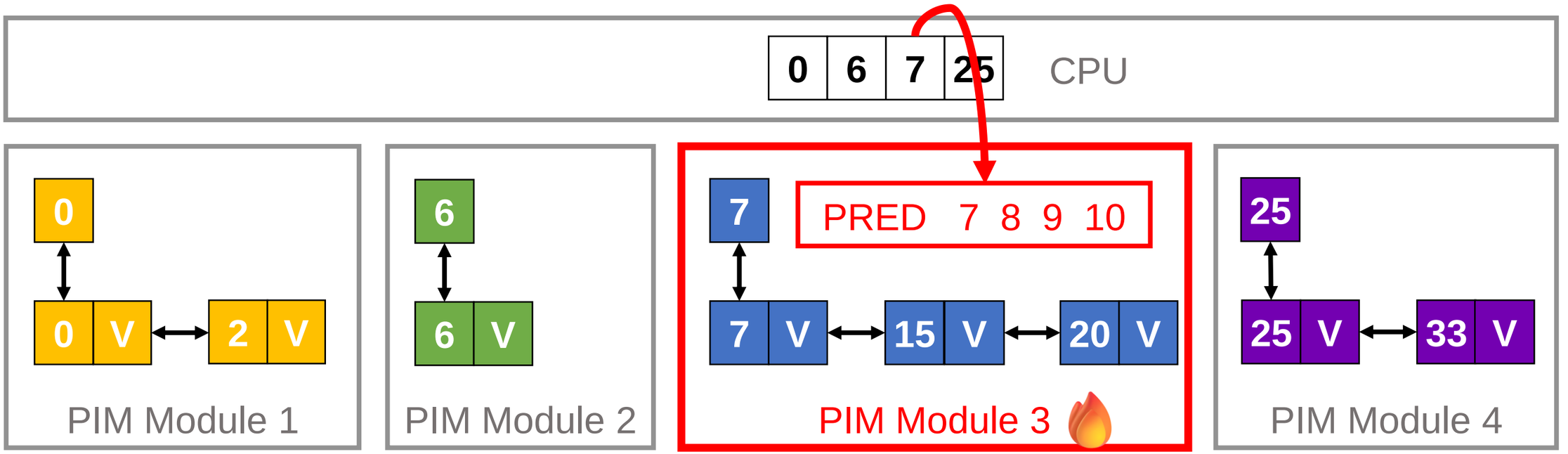

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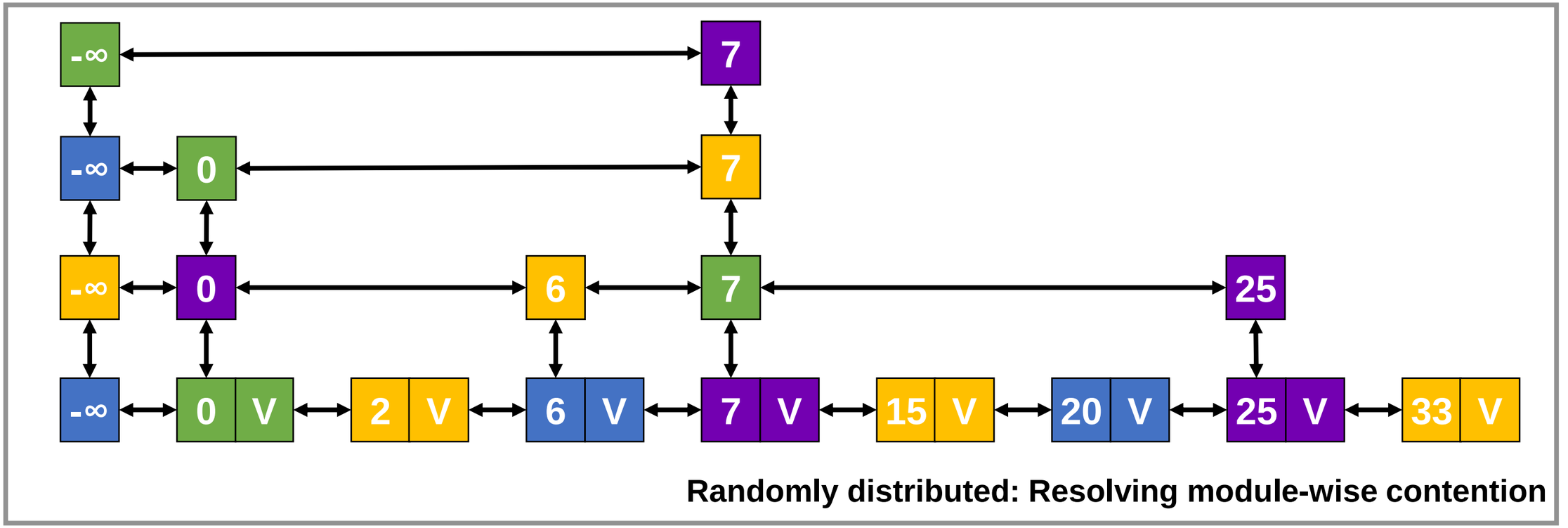
Alternative Approach: Random Mapping

Assuming 4 PIM modules (P = 4 as number of PIM modules)



Pros: Resolving **module-wise contention**

Cons: Does not reduce communication [$O(\log n)$ in trees]

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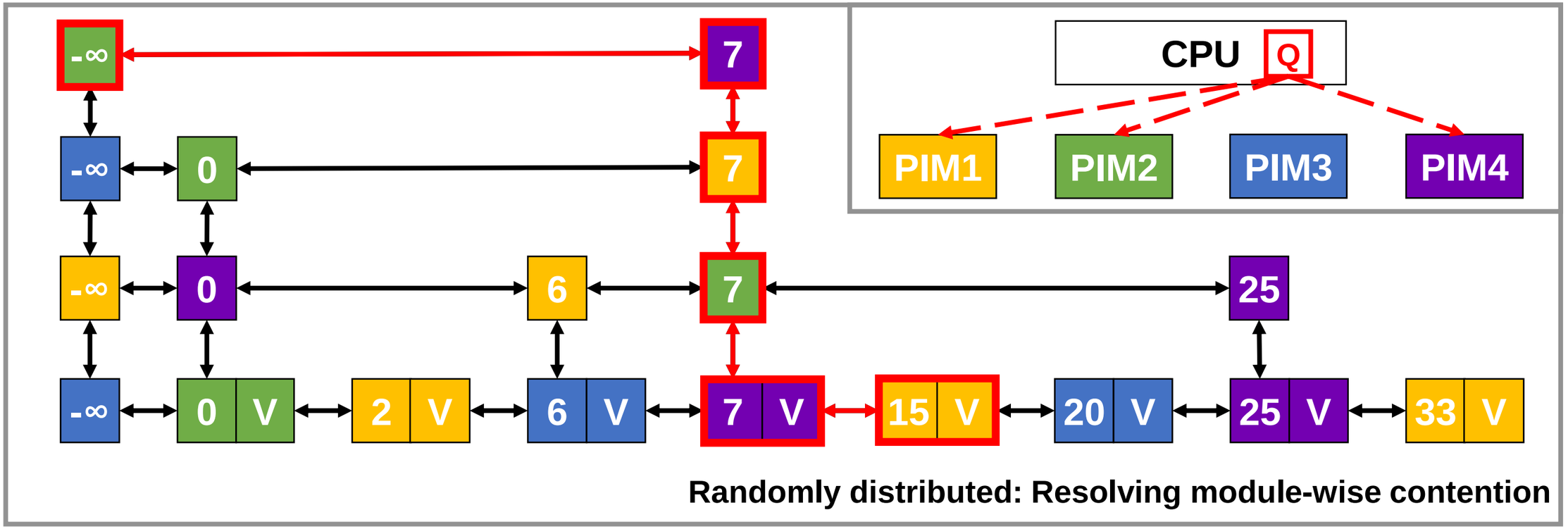

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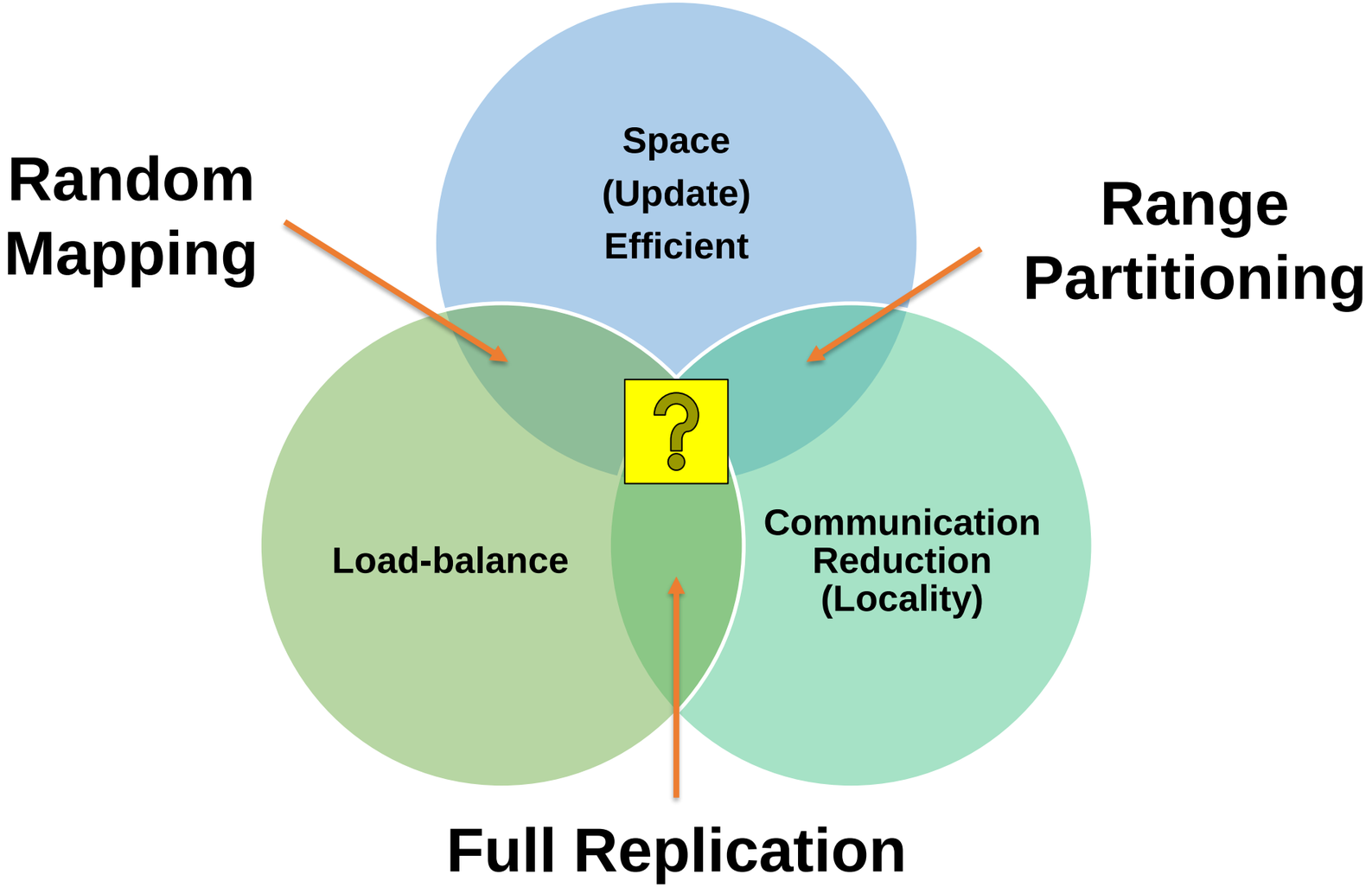
Designing PIM-based indexes



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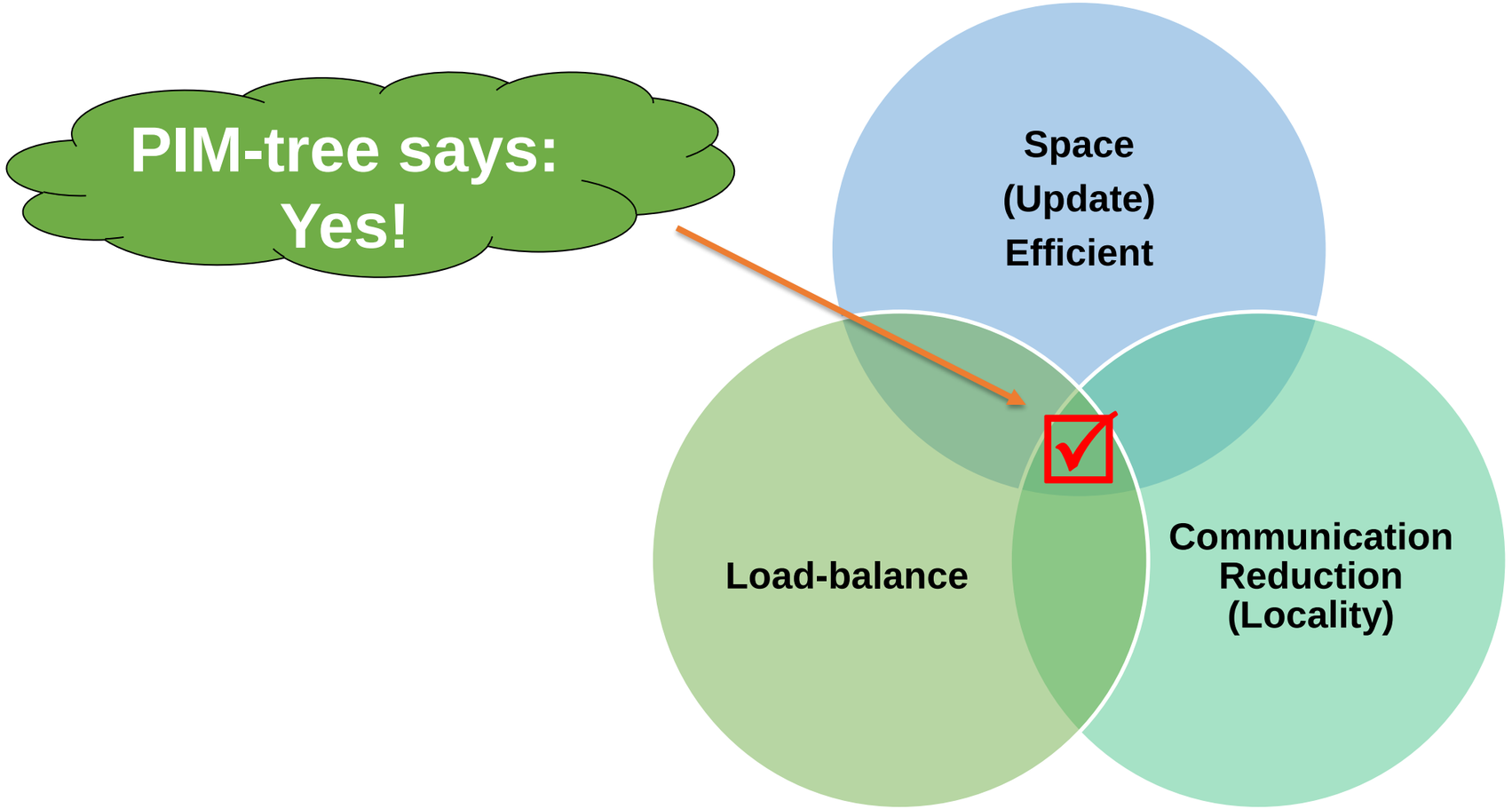


Achieving provable (theoretical) and practical efficiency in throughput, communication and space.

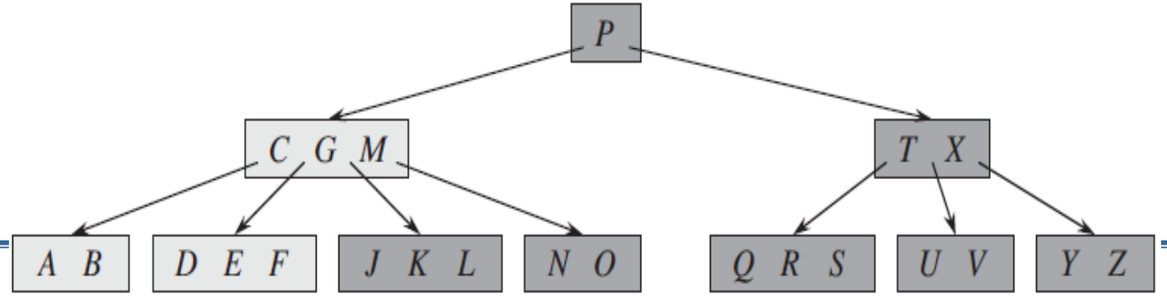
Our Work in a Nutshell

- **Replicated upper part**: From key insights of trees.
- **Push-pull search**: A lightweight design for load balancing.
- **Shadow subtree**: Provide vertical locality.
- **Chunking**: Provide horizontal locality.

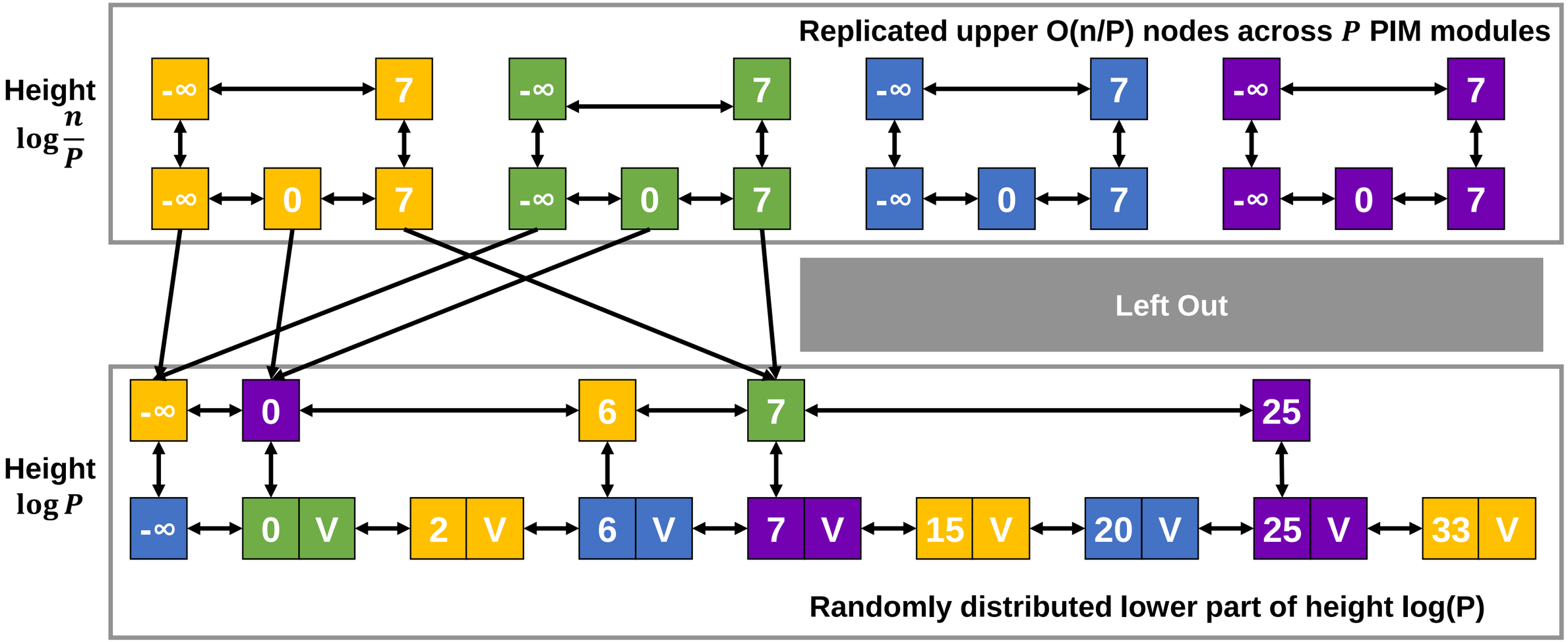
Taking Insight from Trees

- Key Observation in Tree-structured Indexes
  - The upper part of the tree is **frequently accessed** in search queries.
  - The size of the upper part is asymptotically **small**.
  - The upper part is **infrequently updated**.

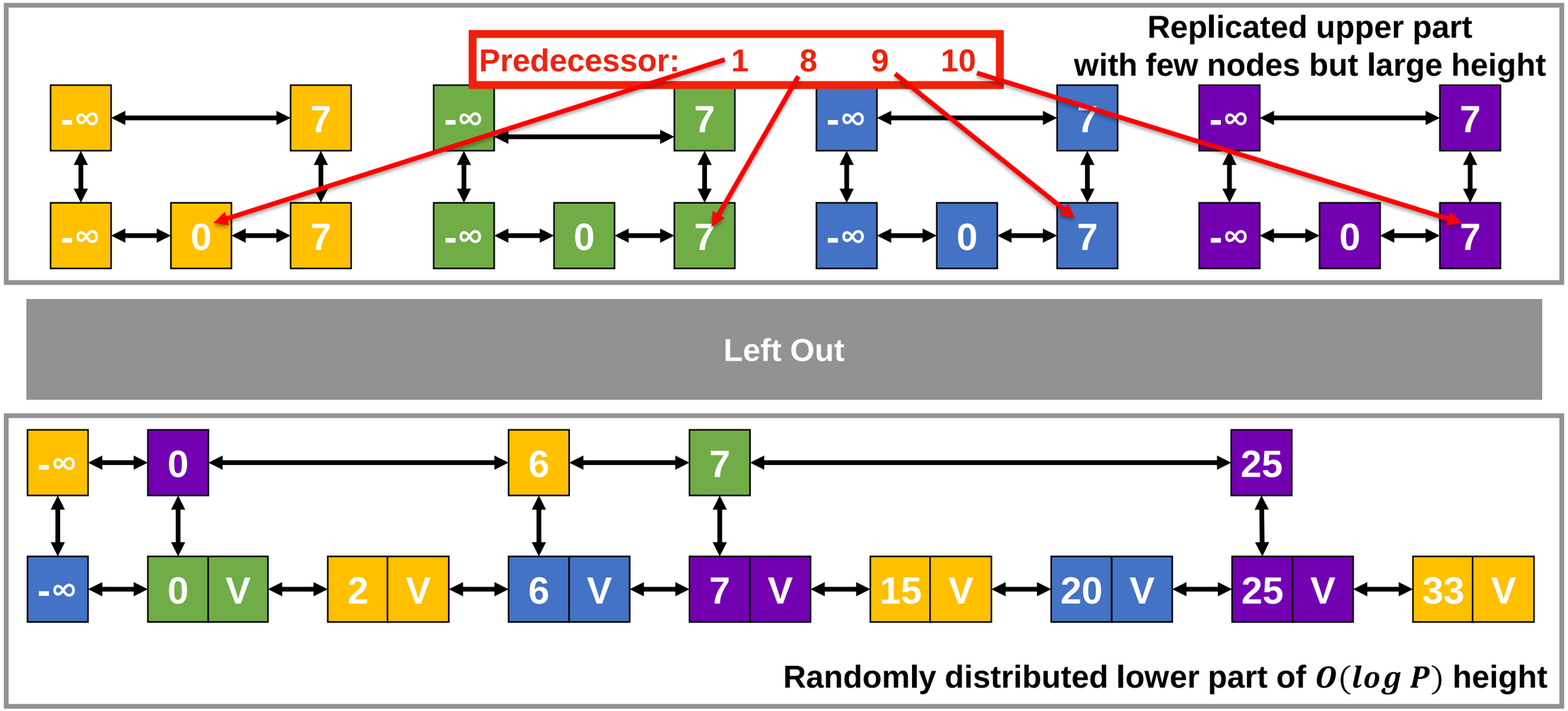
- **Replicating** the upper part in PIM modules should be beneficial.



Two-Layer Structure: Replicated upper part



Powerful Upper Part: Load-balance & Comm.



Low Communication: Only need to communicate $O(\log P)$.

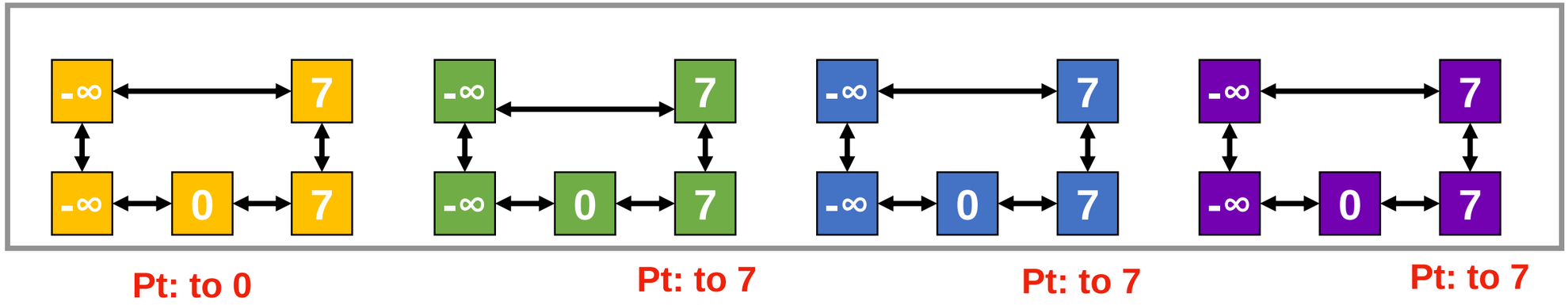
Challenge: Node-wise Contention on Lower Part

CPU side

PIM side

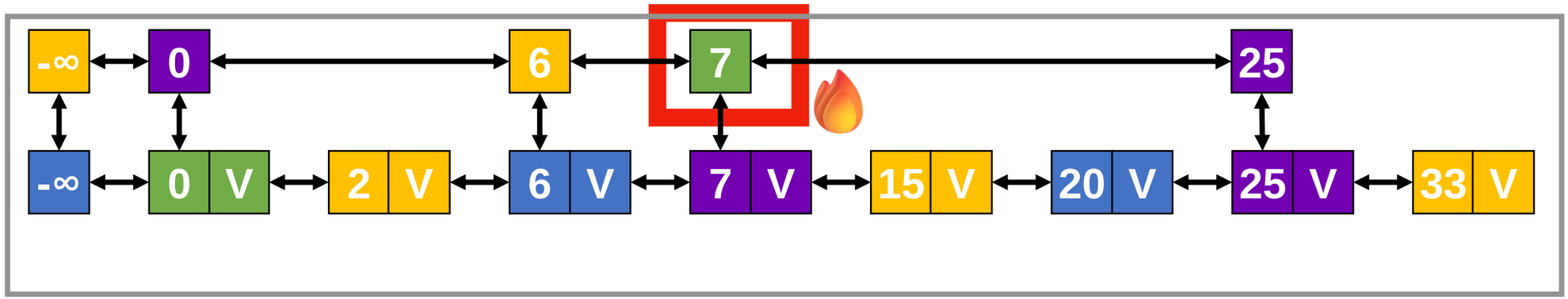
Predecessor:

1 8 9 10



Pt: to 0 Pt: to 7 Pt: to 7 Pt: to 7

1 8 9 10



Solution: Push-Pull Search

CPU side

Predecessor:

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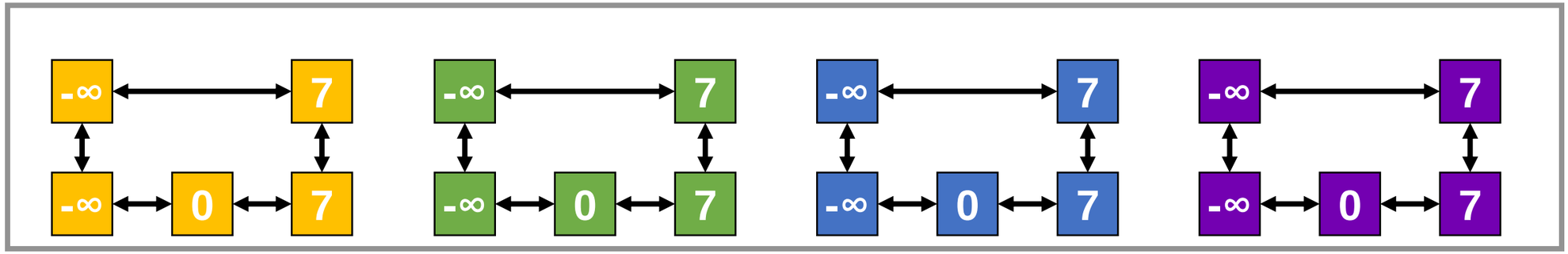
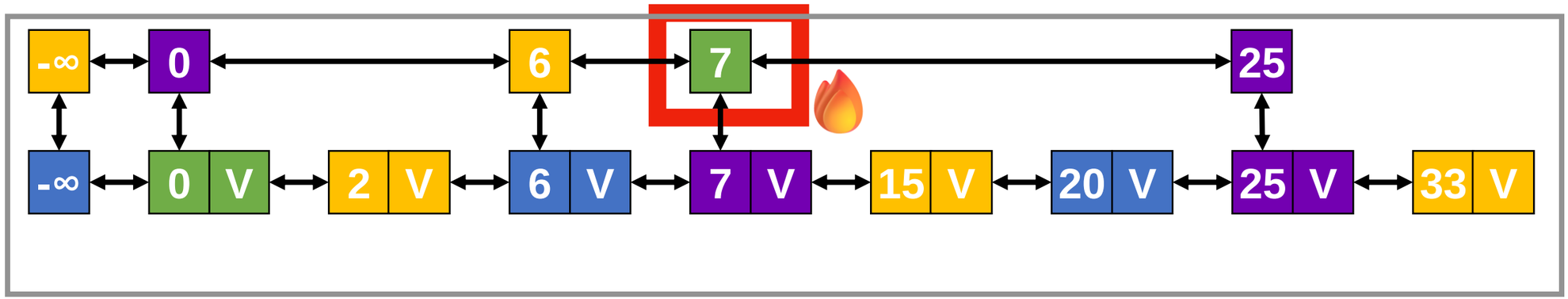
Pull data to CPU

PIM side

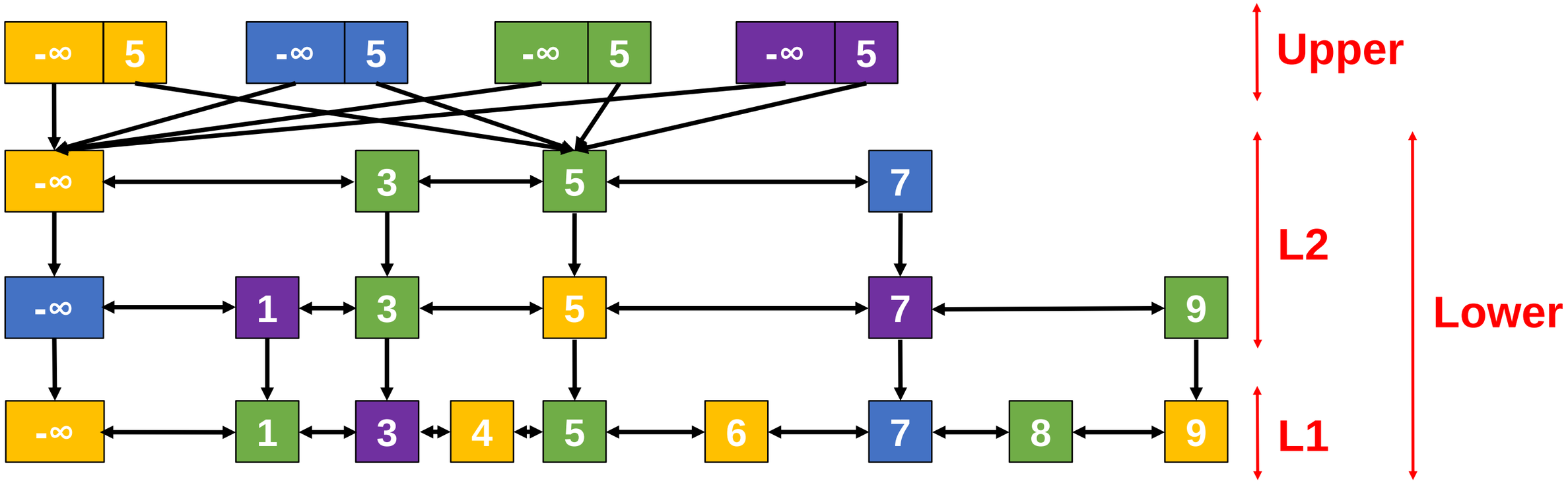


Push computation to PIM



Shadow Subtree: Partial Replication

- Rebuild vertical locality in lower part by **partial** replication.
  - Due to space constraint and update cost.



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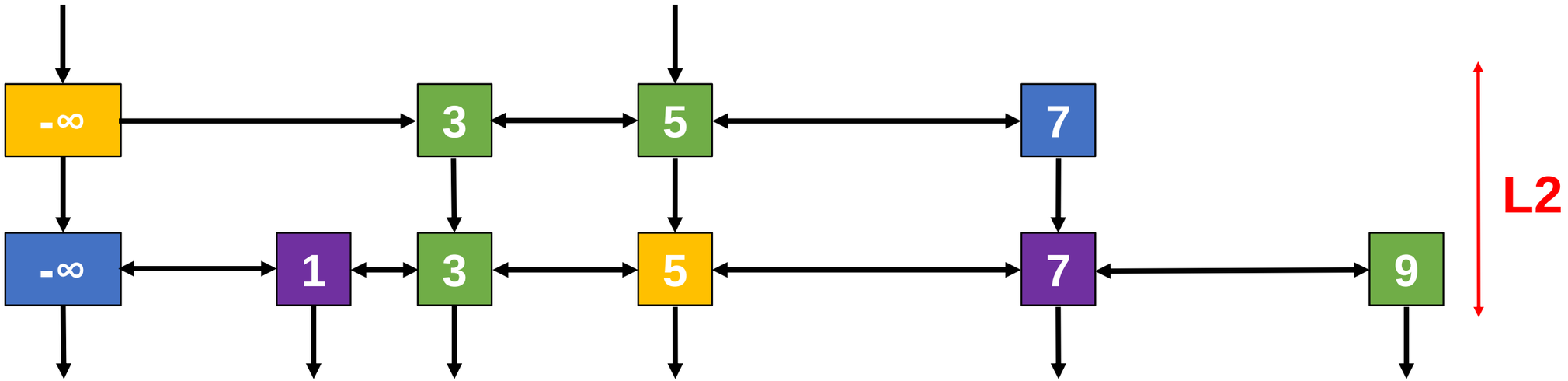

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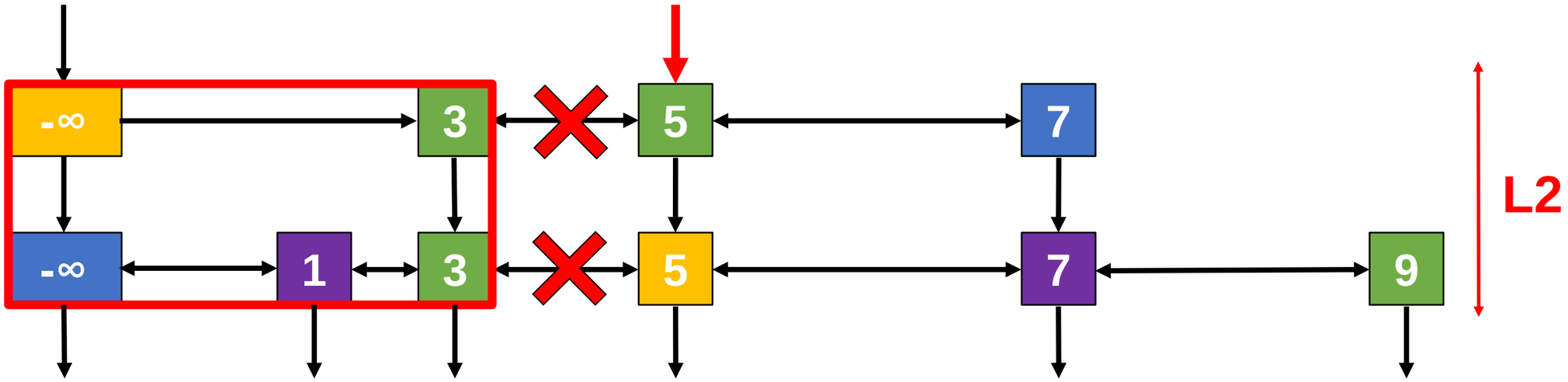

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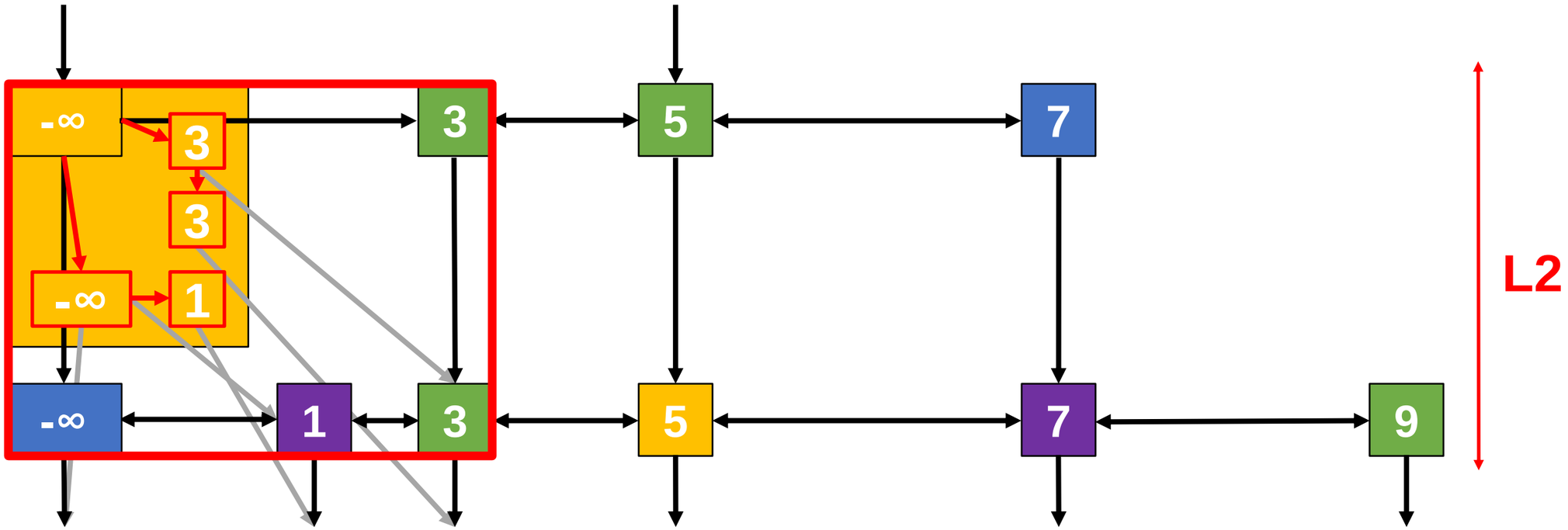

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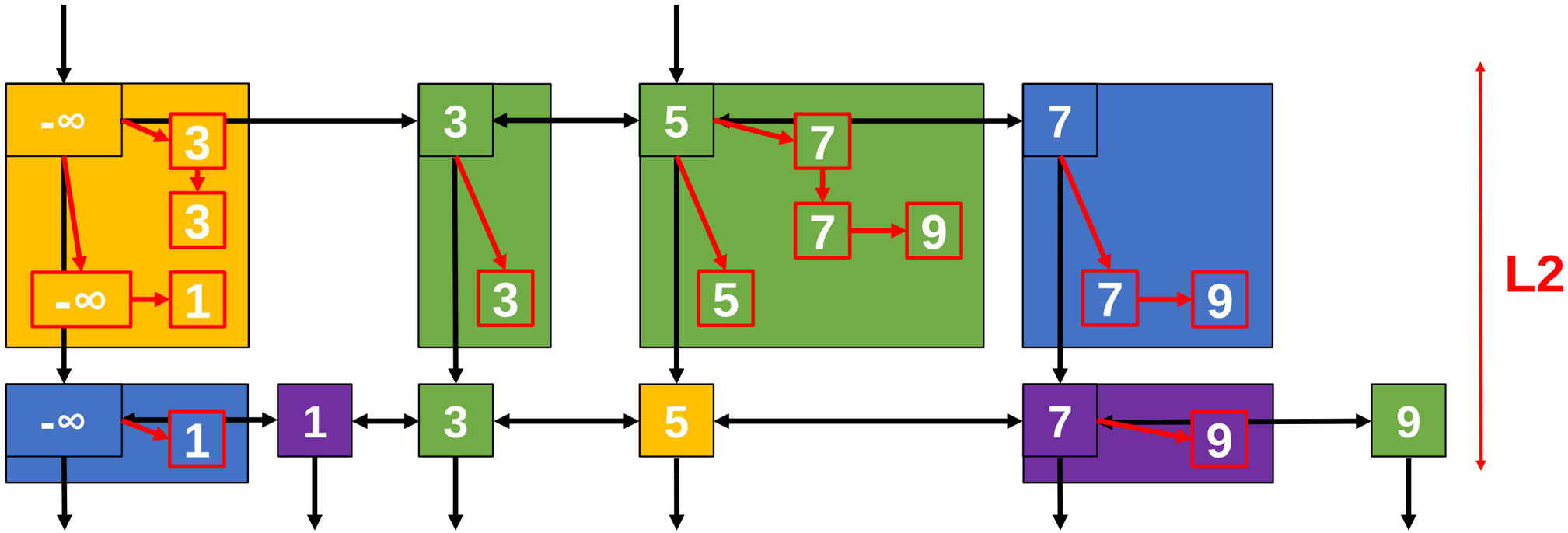

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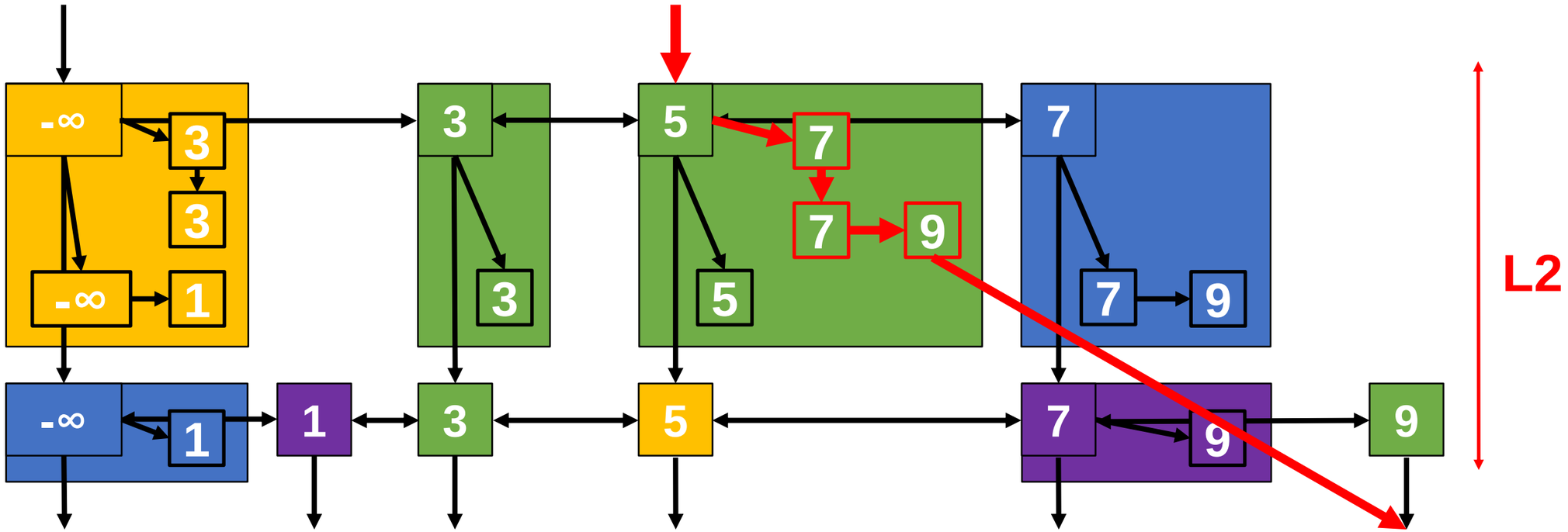
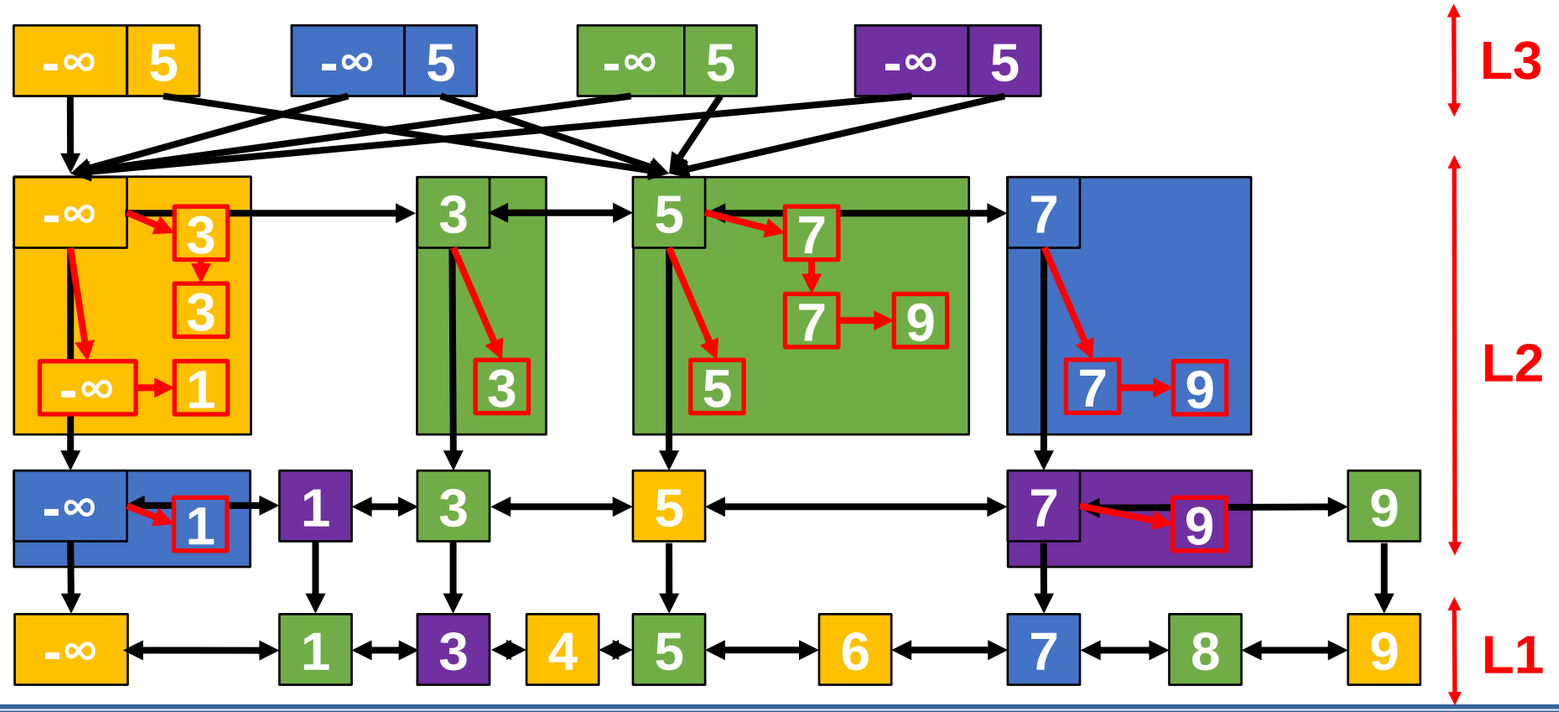


PIM-tree Structure: Three-layer

- Three-layer structure
  - Upper part (L3): **Fully replicated** in all PIM modules.
  - Middle part (L2): **Partially replicated** by Shadow subtree.
  - Lower part (L1): **Distributed** to random PIM modules.



Results of the Three-layer Structure

	L3	L2	L1
Height	$\log n - \log P$	$\log P - \log\log P$	$\log\log P$
Replication Strategy	Full Replication	Shadow Subtree	Distributed
Search Comm. (in words)	$\boldsymbol{O(1)}$	$\boldsymbol{O(1)}$	$\boldsymbol{O(\log\log P)}$
# of Nodes in this layer	$\Theta(n/P)$	$\Theta(n/\log P)$	$\Theta(n)$
# of Replicas per Node	$O(P)$	$O(\log P)$	$O(1)$
Space	$\Theta(n)$	$\Theta(n)$	$\Theta(n)$
Update Frequency	$1/P$	$1/\log P$	1
Update Comm. (post search)	$\boldsymbol{O(1)}$	$\boldsymbol{O(1)}$	$\boldsymbol{O(1)}$

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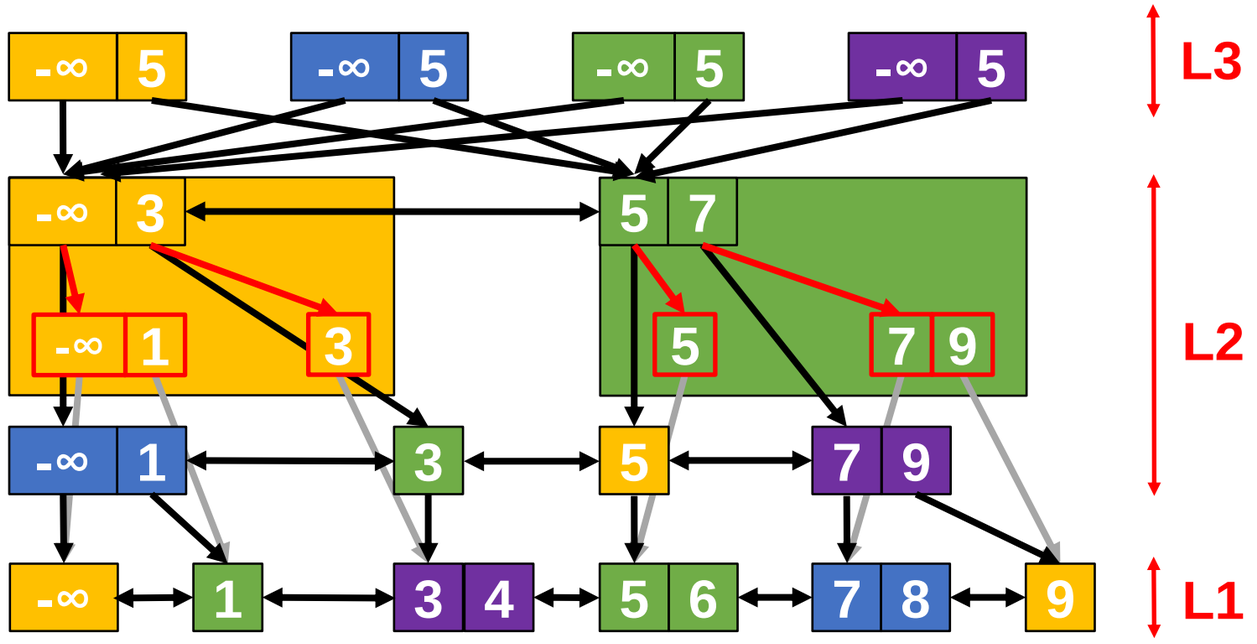
Chunking : Further Horizontal Locality

- In the lower part, merge horizontal nodes chunks. stored on one PIM module.
- Cut all <u>horizontal</u> inter-module communication.
- Expected chunk size: B
  - Typically $B = 16$



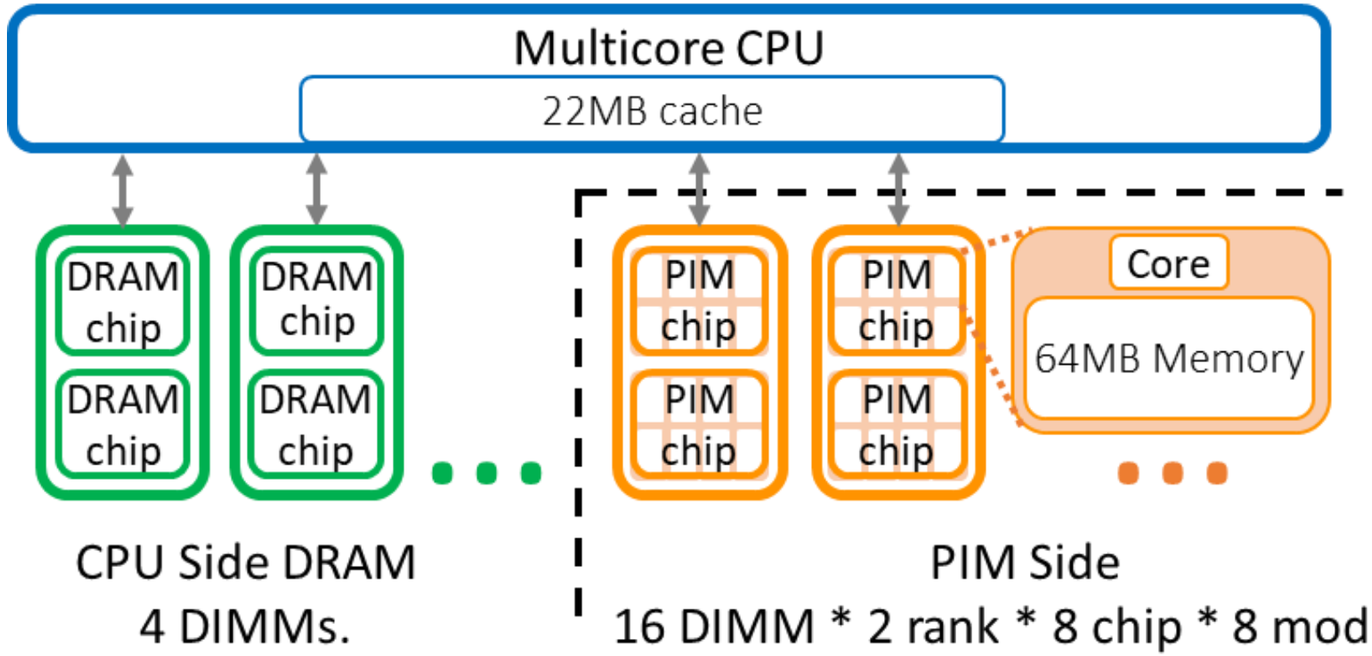
Results in The PIM Model

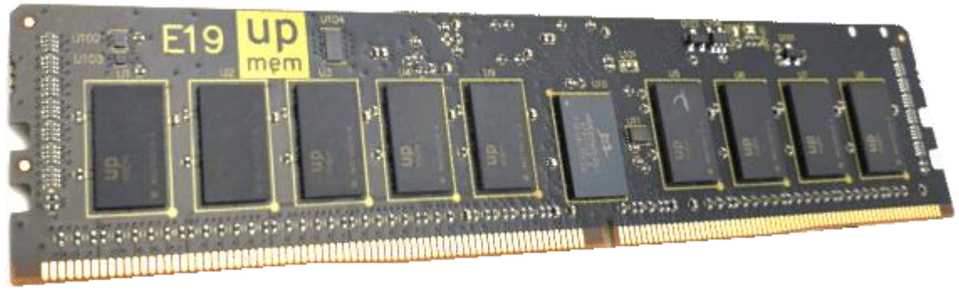
- Load-balance guaranteed* against adversary
- Reduced Communication <u>regardless of skew</u>
  - $\boldsymbol{O(\log_B \log_B P)}$ per operation for both search and update
  - 3 or 4 communication rounds in practice
- Linear space consumption $\Theta(n)$

* With high probability if the batch size is large enough.

Experimental Platform

- Upmem tech: https://www.upmem.com



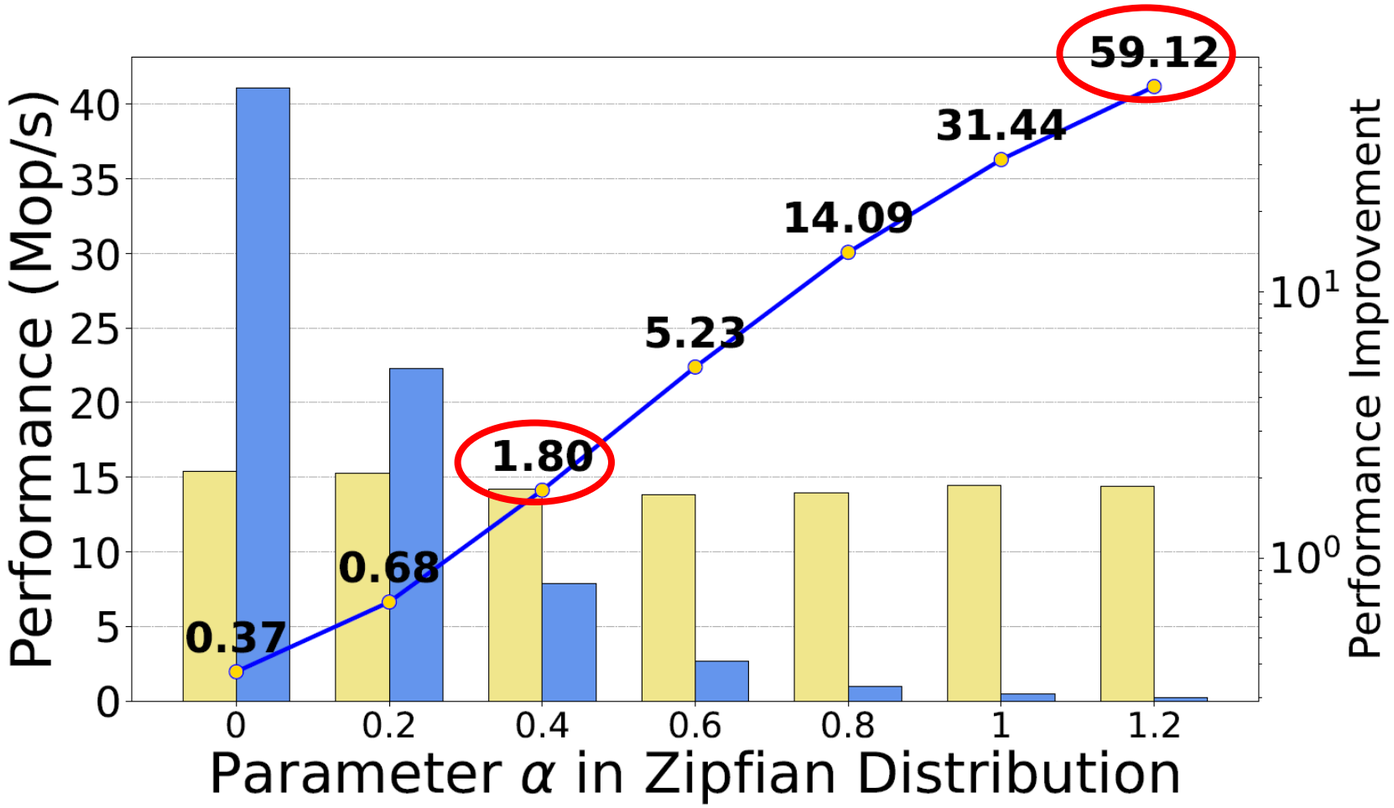


256GB in total.

Each PIM core is a 32-bit RISC processor @450MHz.

In this architecture, scheduling of PIM modules are done by the user program.

Results Comparing with Prior PIM-based Indexes



Predecessor() **Throughput**
on Zipf workloads

PIM-Tree

Partitioned Skip List

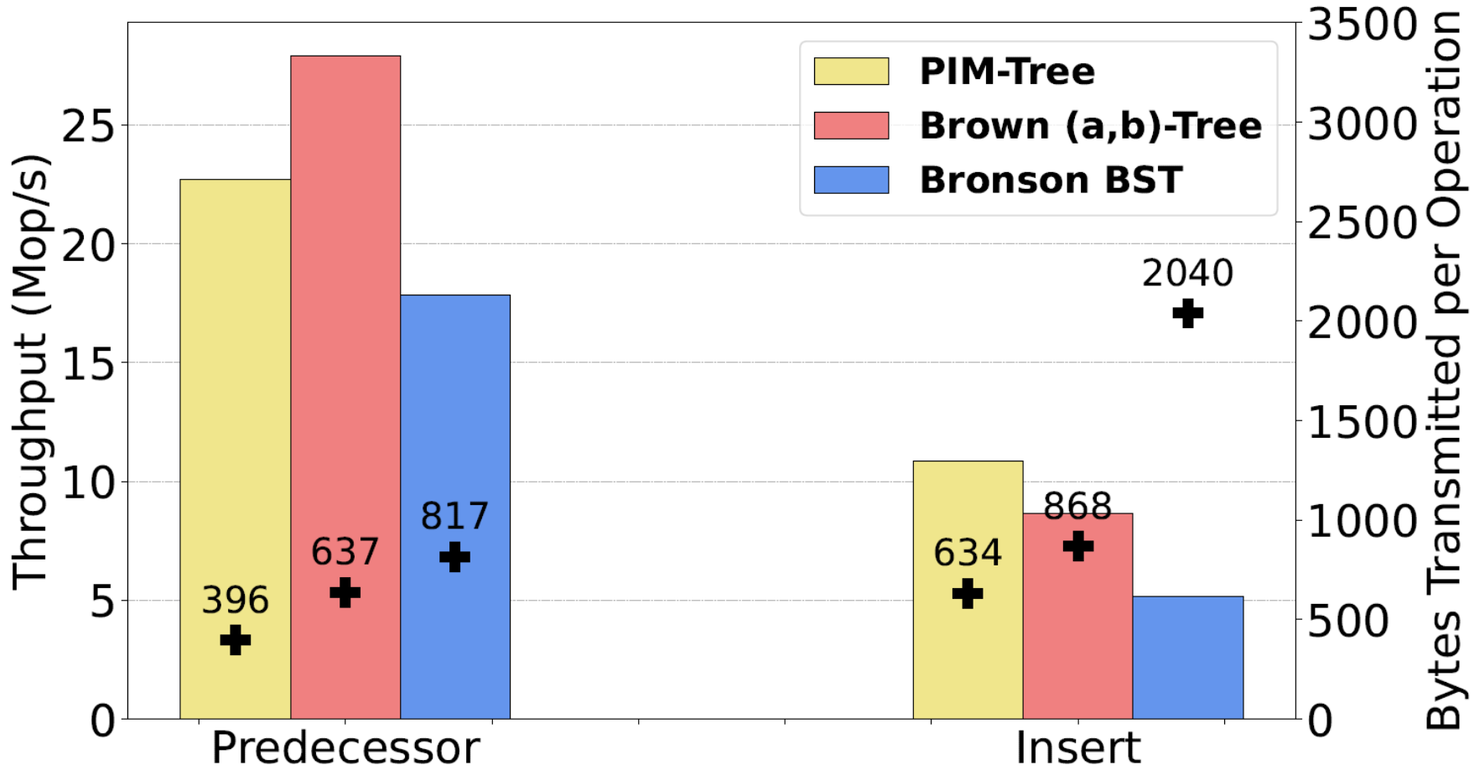
Improvements of PIM-Tree over Partitioned Skip List

Up to 59X improvement !

Results Comparing with CPU-based Indexes

Experiments on Wikipedia dataset Over SOTA Shared-memory Indexes

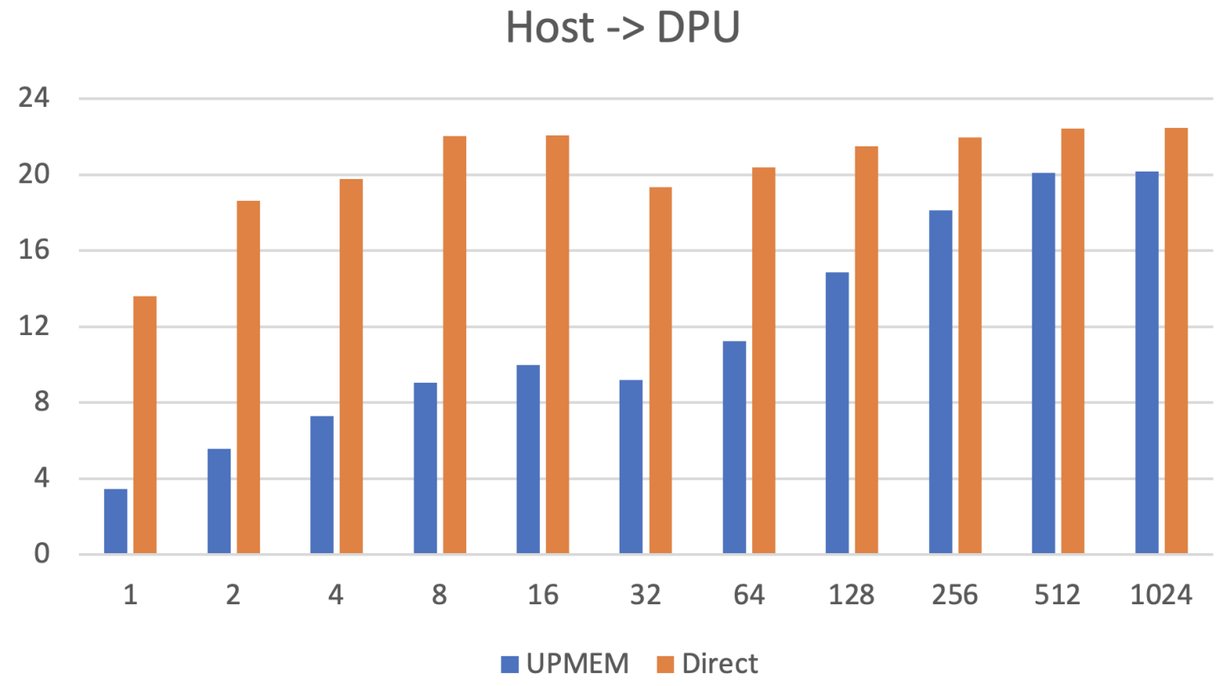
* Bars are throughputs; '+' are communications

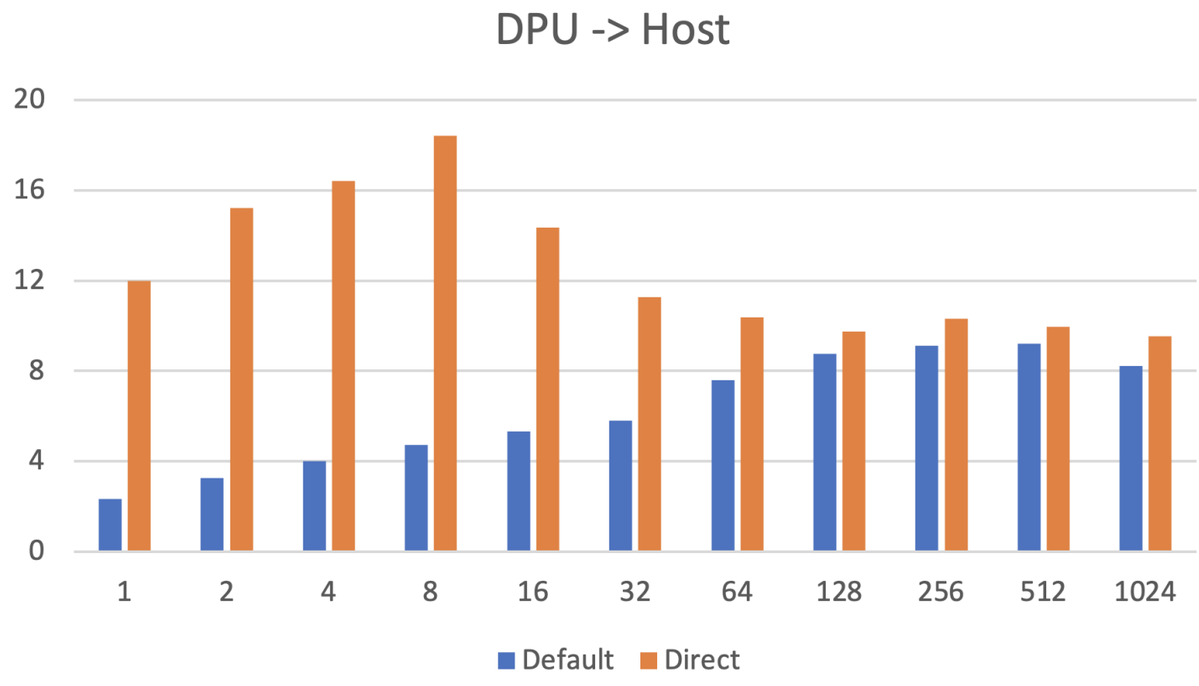


Less communication, faster inserts

New Early-Stage Results in Bandwidth

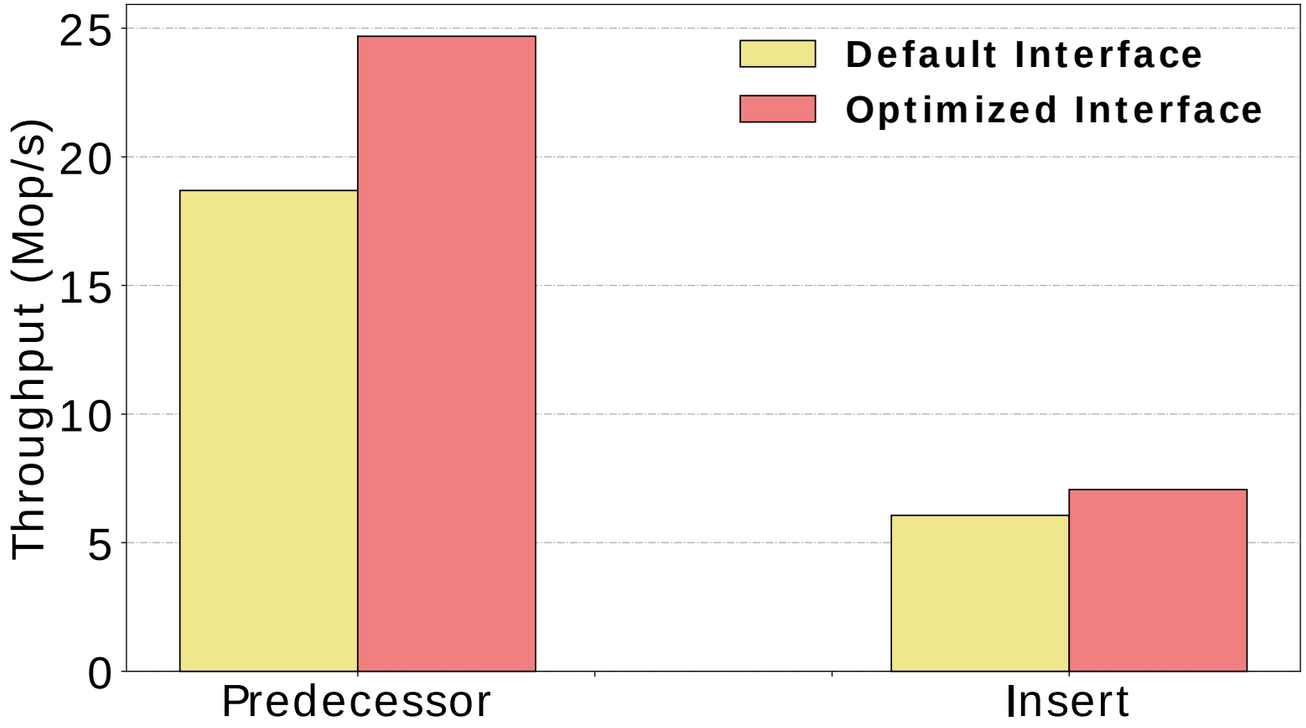
- Optimize communication for small batches
- Scatter/Gather buffers of 1~1024 KB with all DPUs
  - 32 ranks, 2000 PIM modules functioning





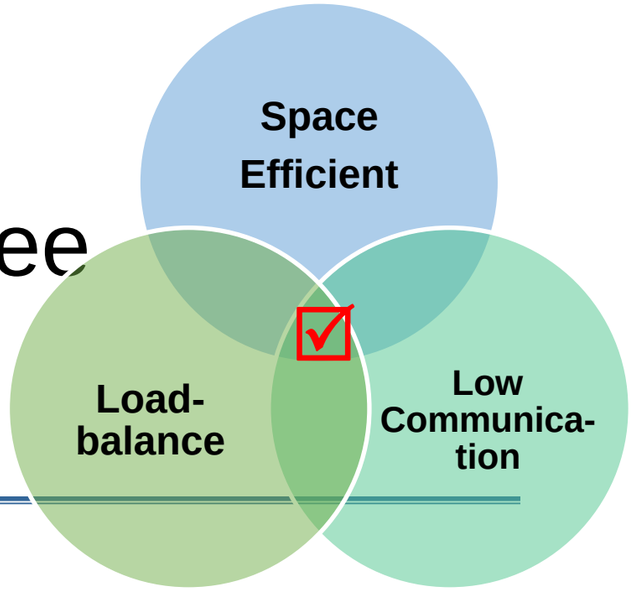
New Early-Stage Results in Throughput

- Applying new interface on Wikipedia dataset
  - 32 ranks, 2000 PIM modules functioning
  - upmem-sdk-light
    @ github

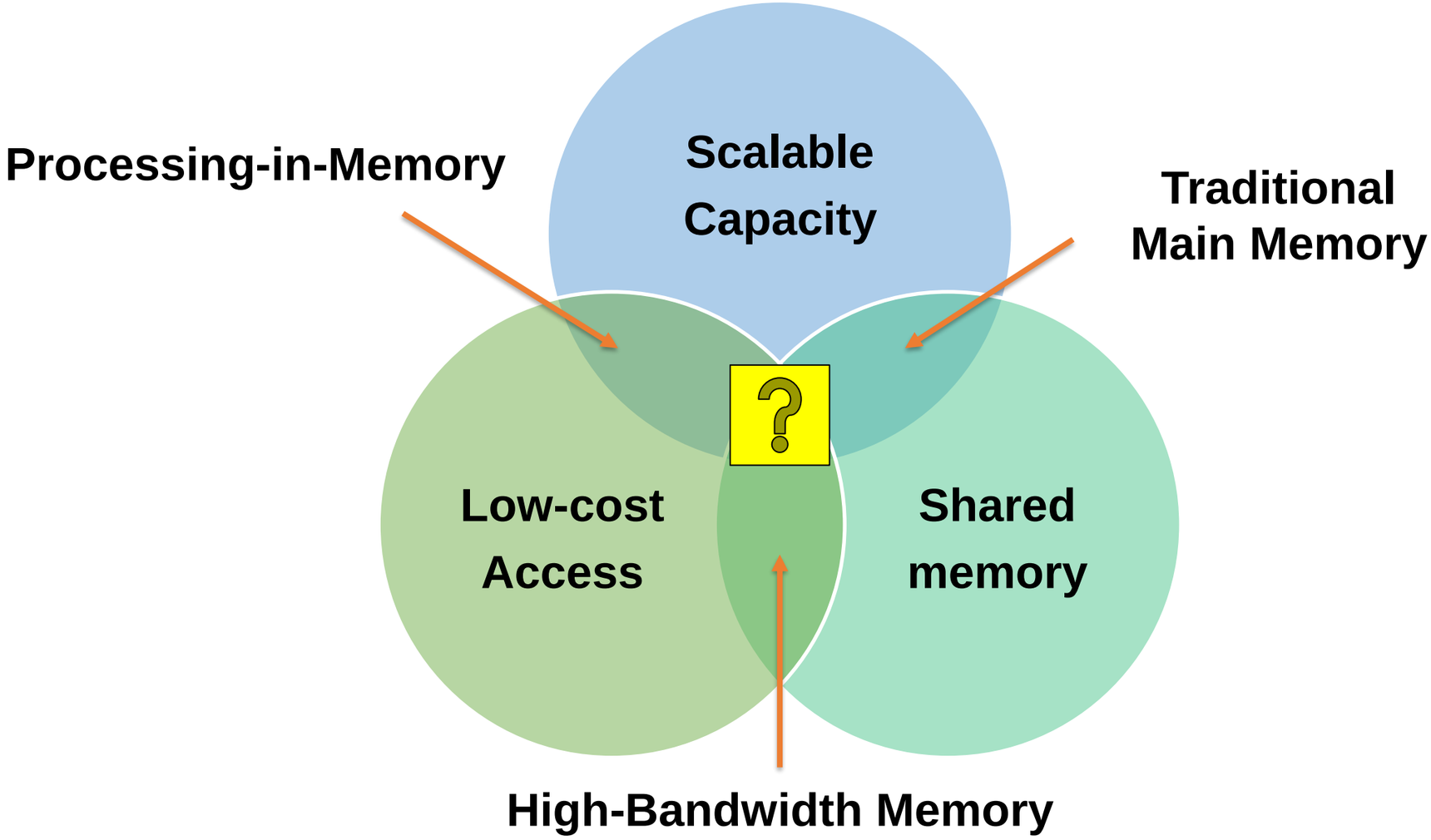


Key Takeaways

- PIM emerging as means of reducing data movement
- Prior works of PIM indexes vulnerable to skew
- PIM-tree is a skew-resistant database index
  - Three-level Structure: Different replication strategies
  - Push-pull search: Lightweight load balance
  - Chunking: Further reduction on communication
  - Provable and practical efficiency
- Codes: https://github.com/cmuparlay/PIM-tree



Ideal Memory



B-tree? Skip lists?

- Both are used in practice
  - Skip lists used in the memory part for LSM trees
- We believe our optimizations apply to both
  - B-tree can be interesting future work.
- In our implementation
  - L3 is implemented by a b-tree
  - L2 and L1 are implemented by skip lists
    - Enables easier parallel inserts/deletes