ME-HPTs: Memory-Efficient Hashed Page Tables

HPCA 2023

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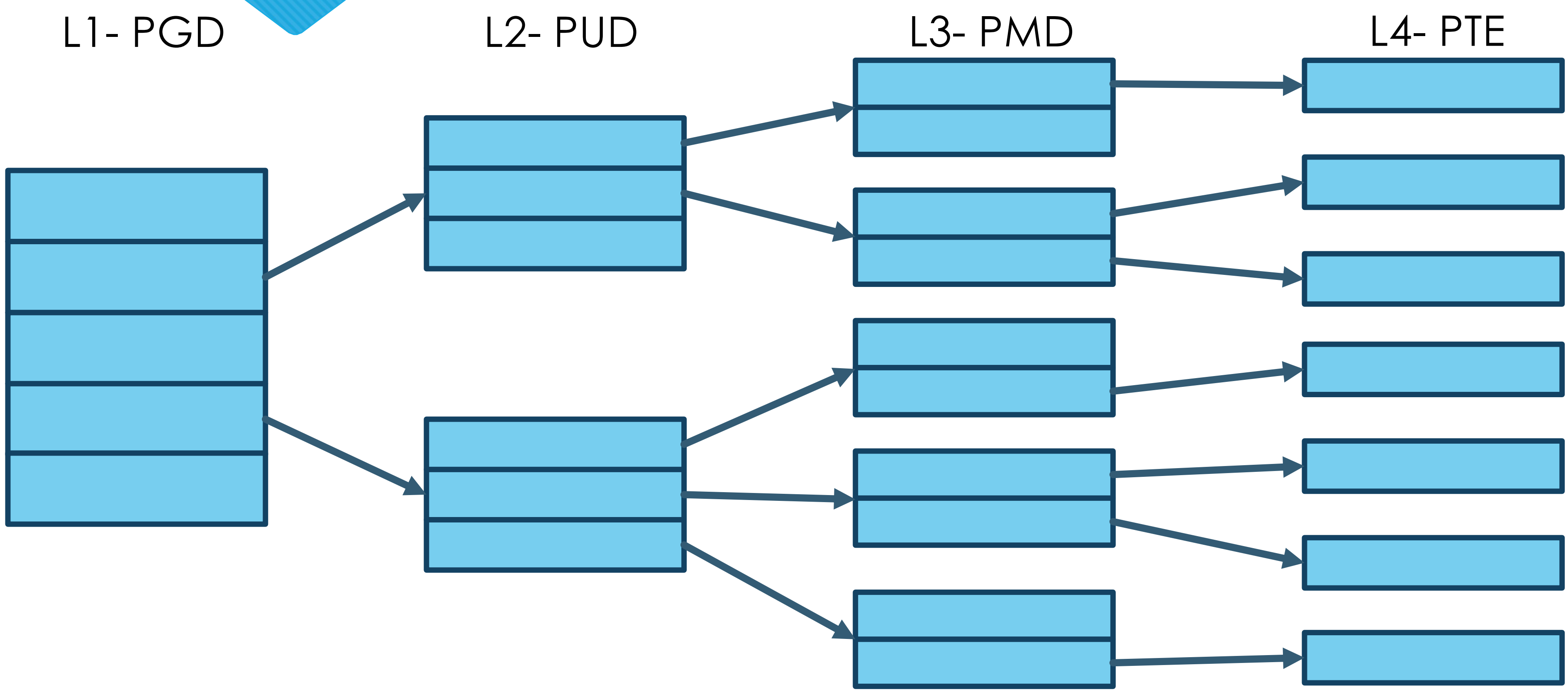
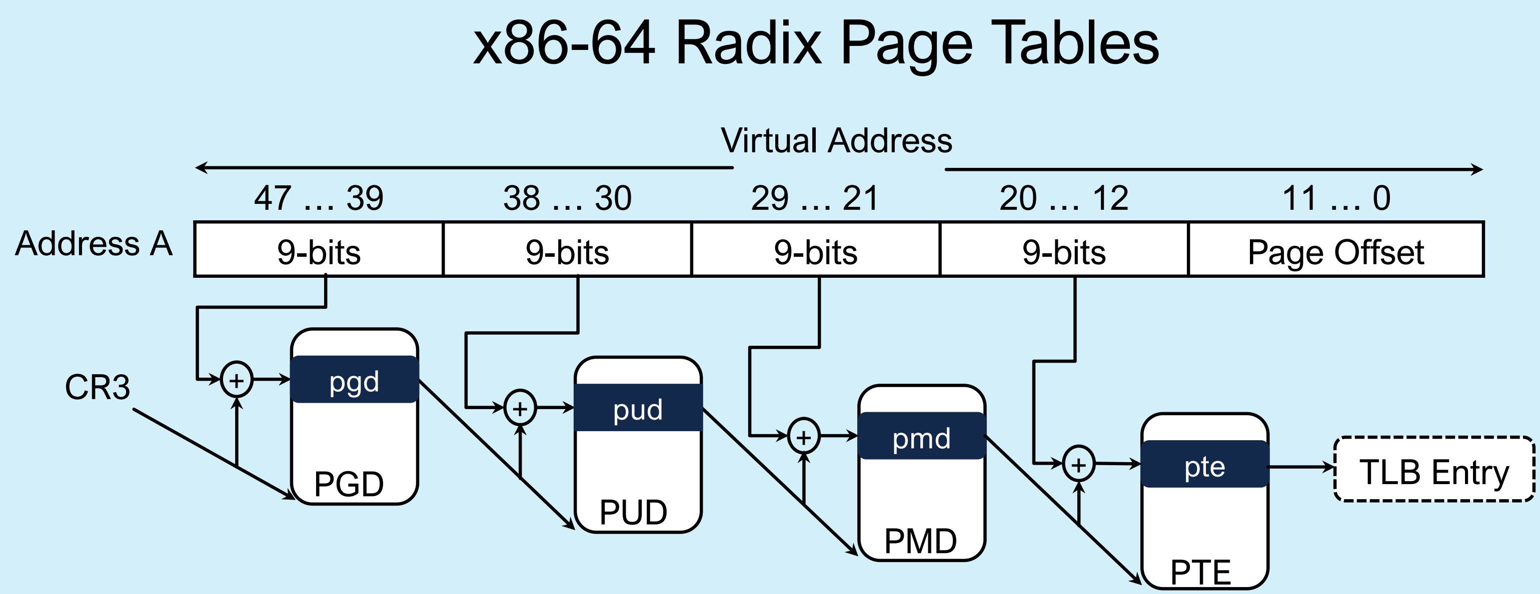
Virtual Memory and Page Tables

- Virtual memory is an essential technique in modern computing systems
  - Memory virtualization
  - Process isolation
- Virtual memory performance depends on the page table organization
  - Radix page tables – slow and not scalable
  - Hashed page tables – memory inefficient

Radix Page Tables: Memory-Efficient Multi-Level Trees

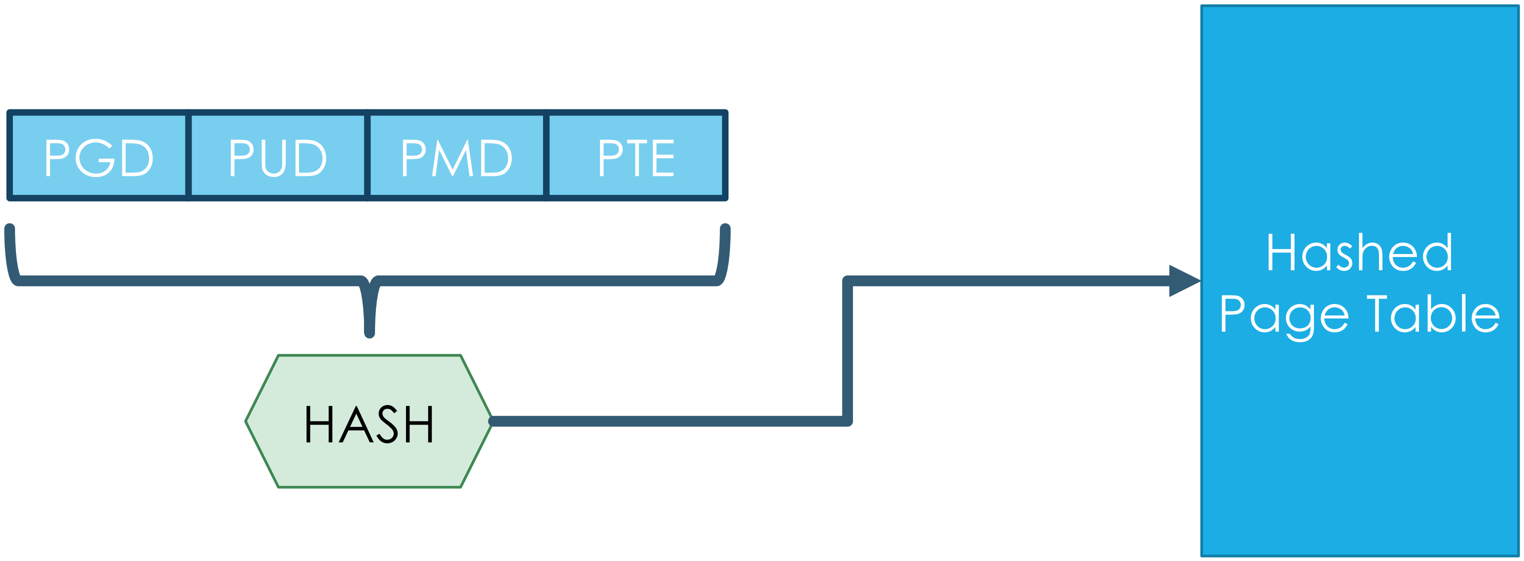


Radix Page Walk: Expensive Pointer Chase



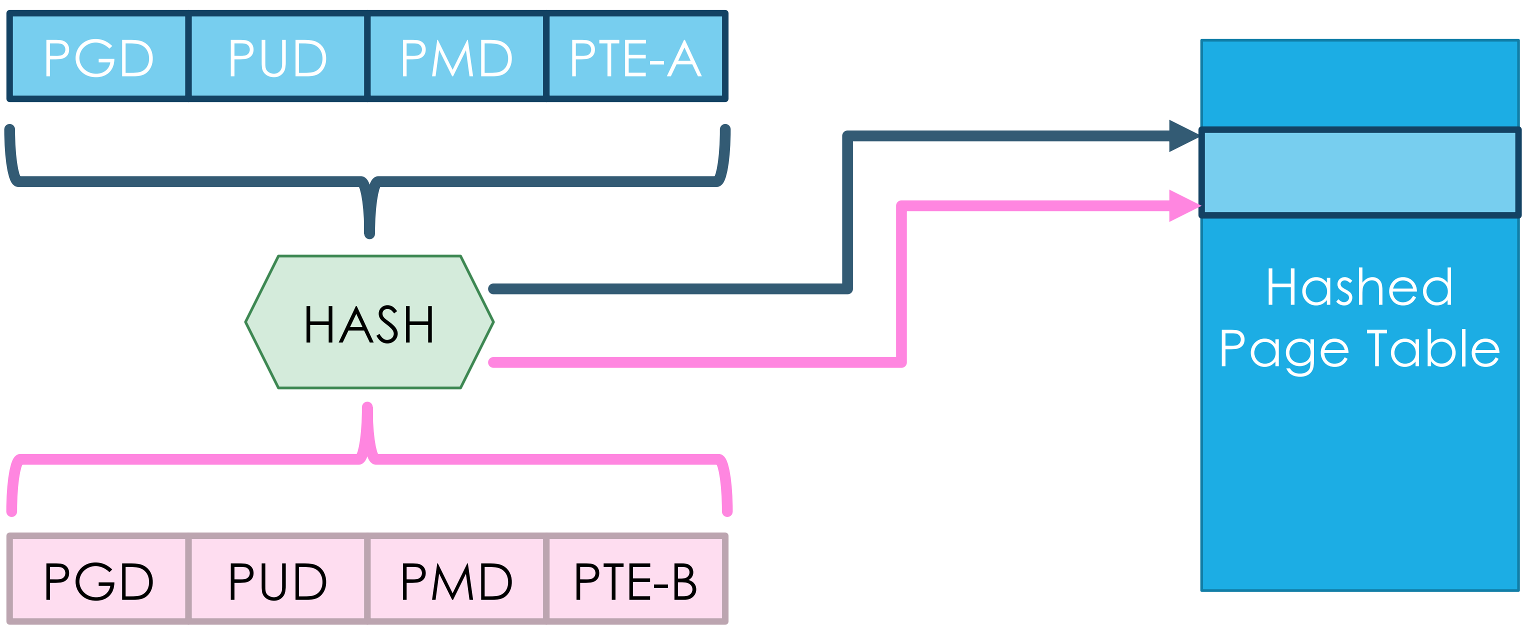
Hashed Page Tables

Page walk requires a single memory access



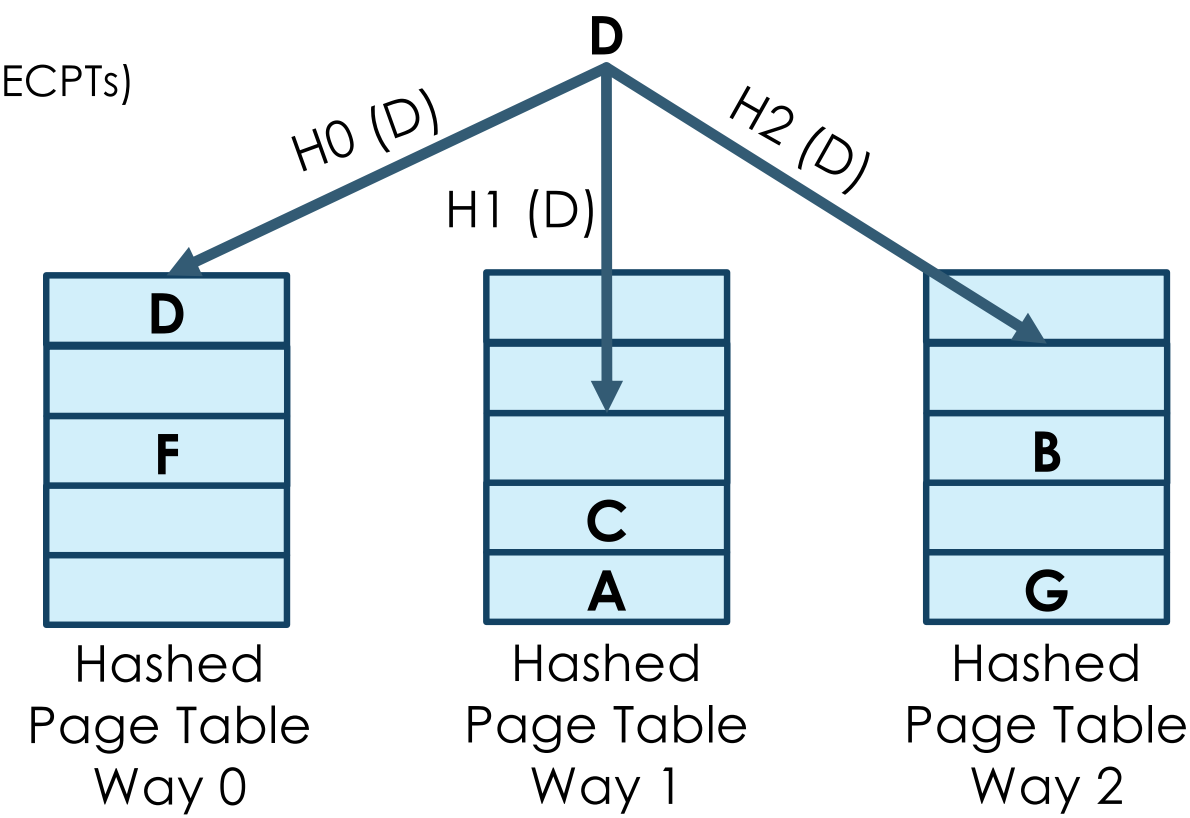
Hashed Page Tables

Hash collisions



Hashed Page Tables: Recent Advances Make Them Compelling

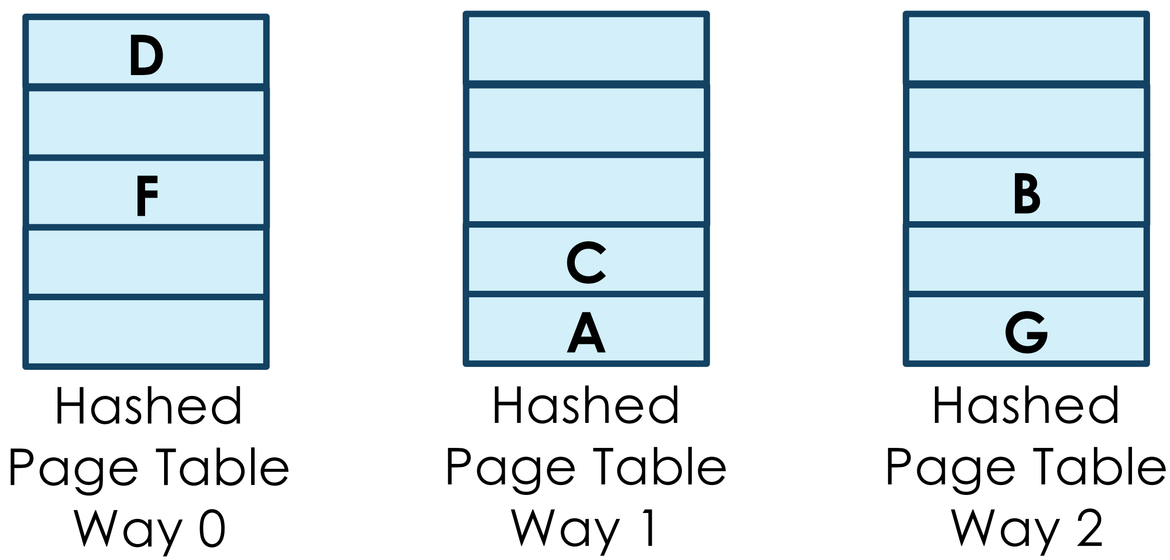
Elastic Cuckoo Page Tables (ECPTs)



Hashed Page Tables: Recent Advances Make Them Compelling

Cuckoo Hashing

Insert E



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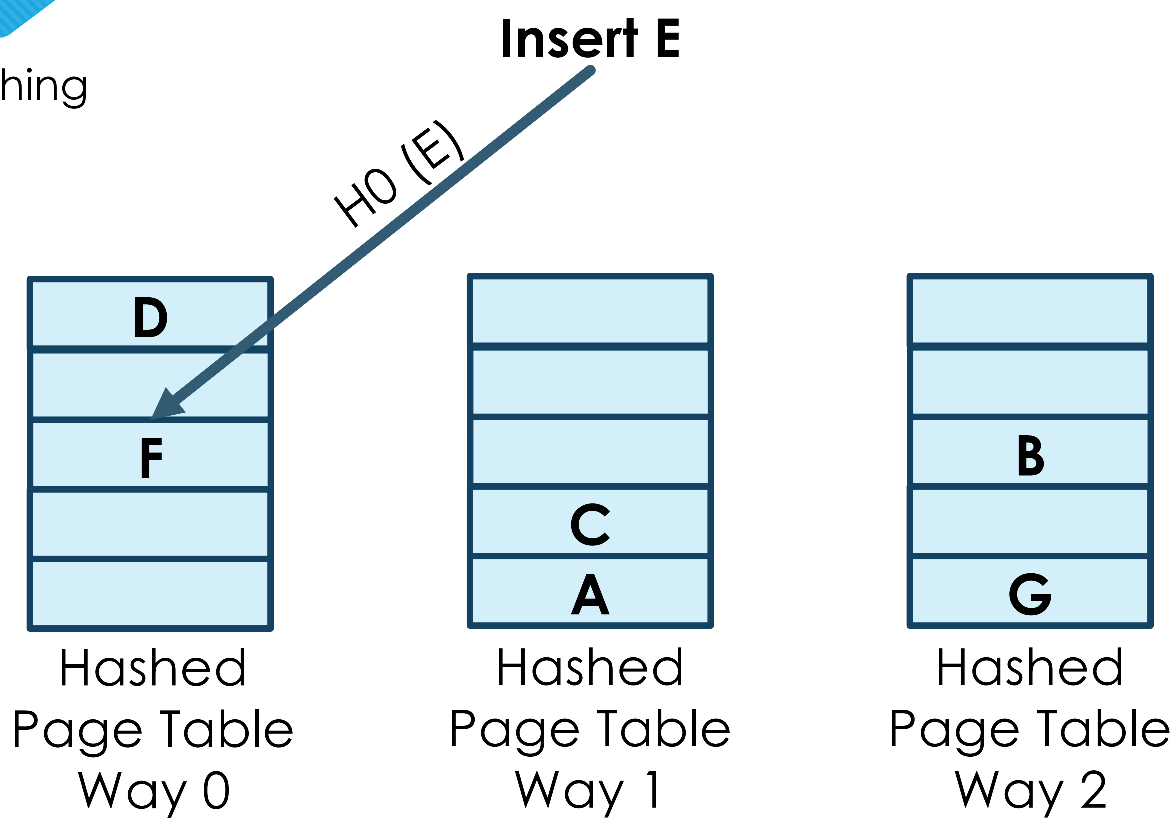

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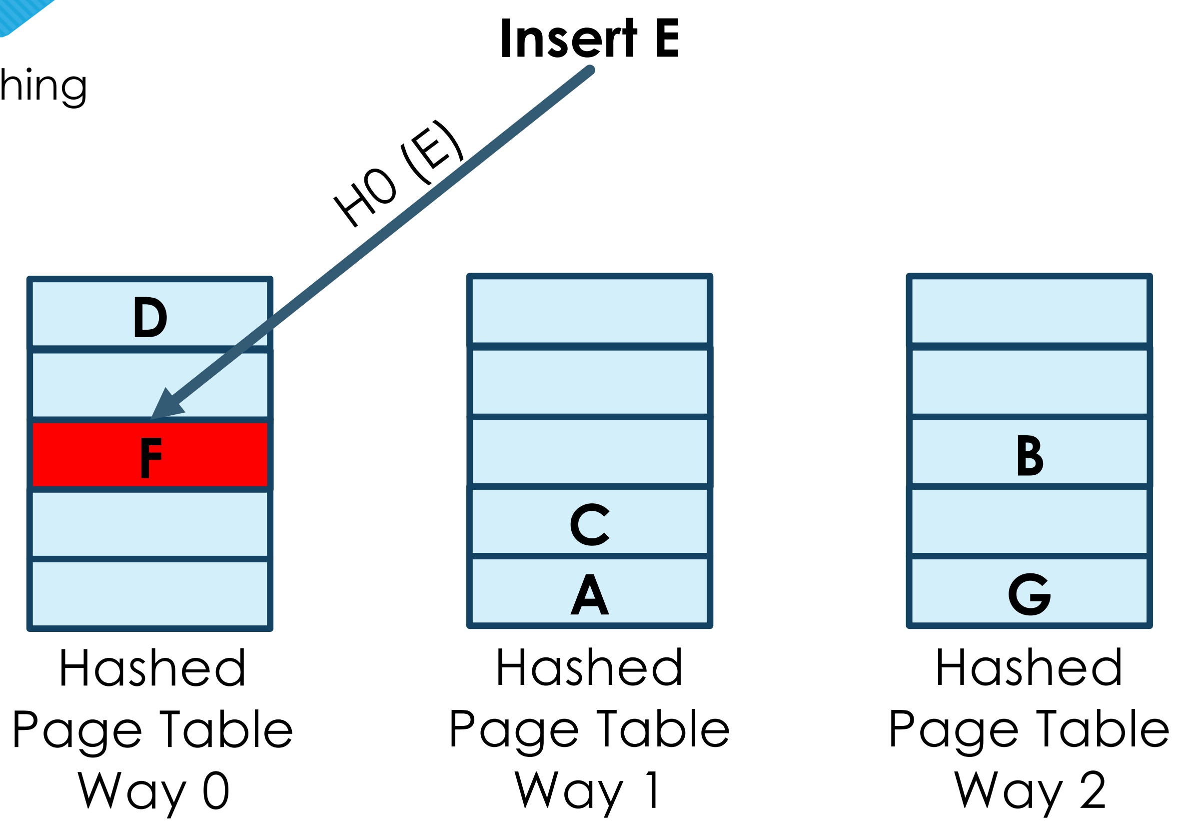

Hashed Page Tables:
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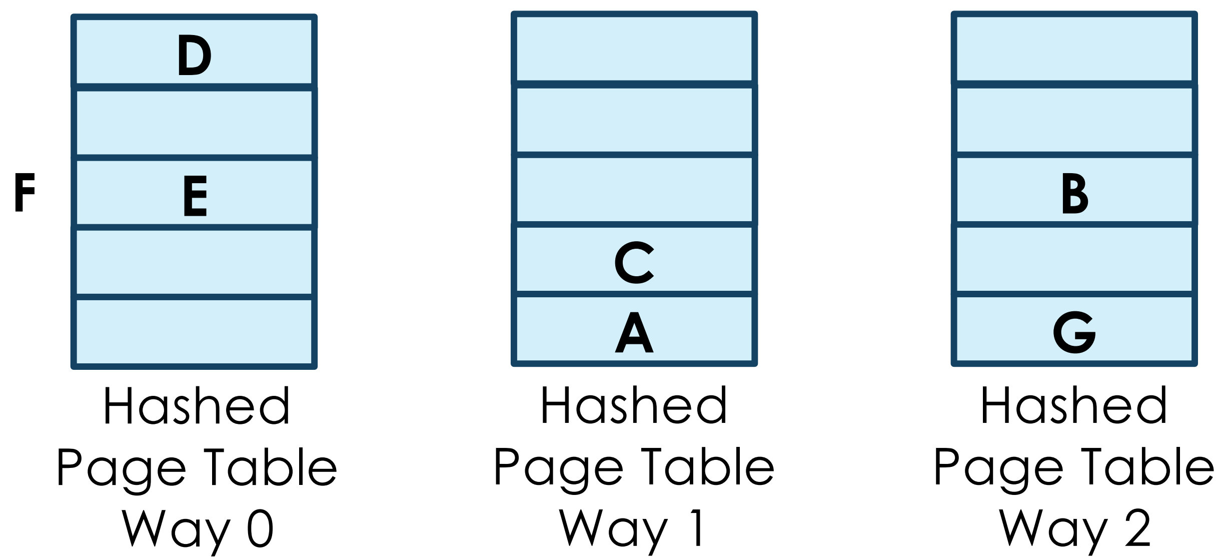
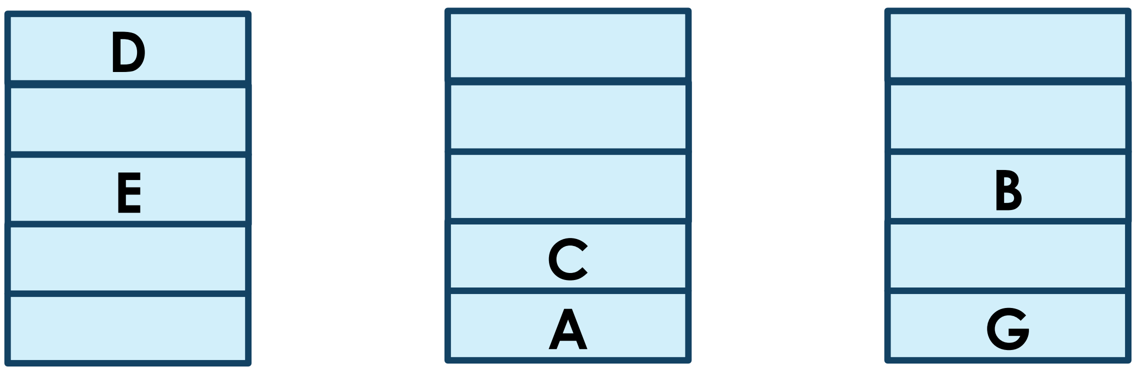
Cuckoo Hashing



Hashed Page Tables: Recent Advances Make Them Compelling

Cuckoo Hashing

Insert F



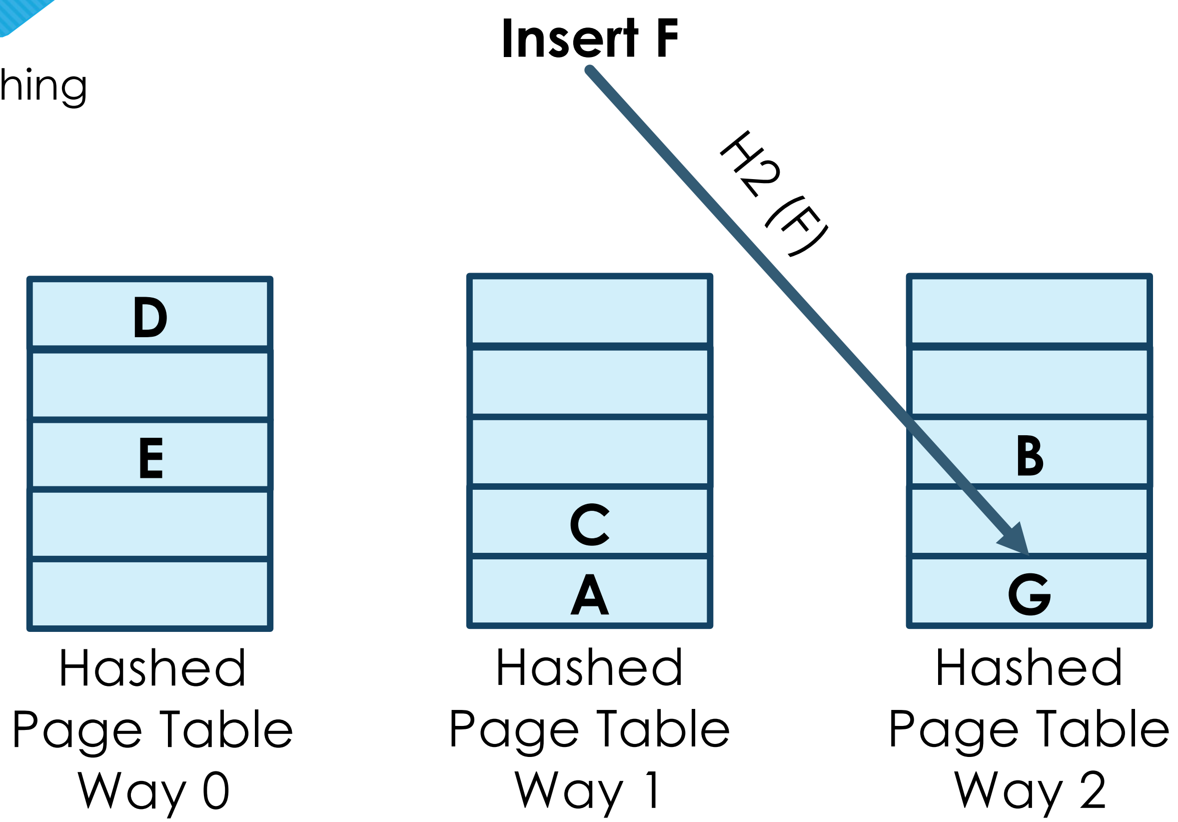
Hashed Page Table Way 0

Hashed Page Table Way 1

Hashed Page Table Way 2

Hashed Page Tables: Recent Advances Make Them Compelling

Cuckoo Hashing



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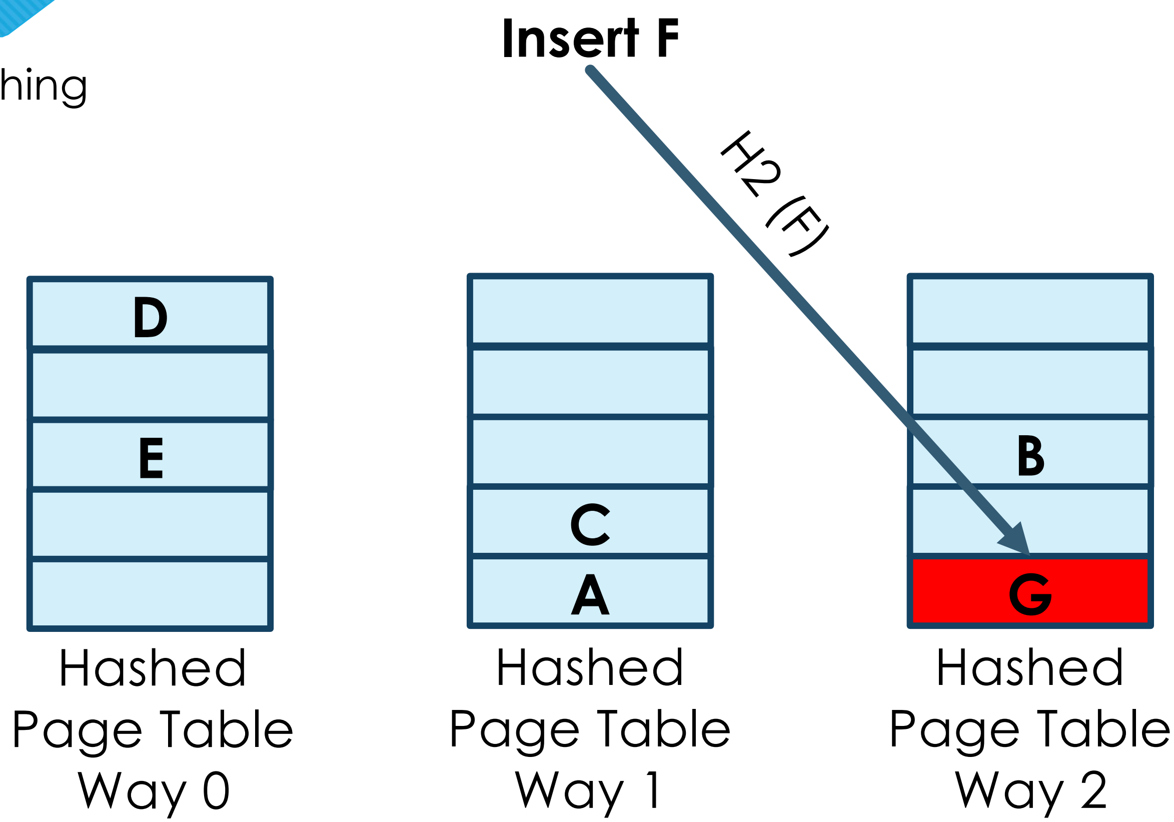

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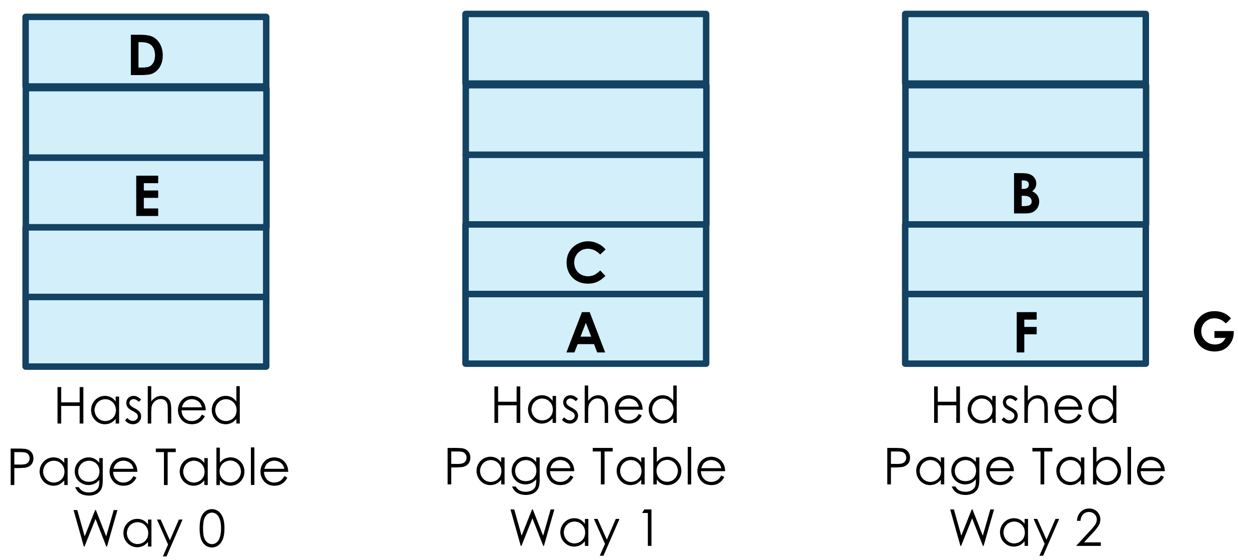
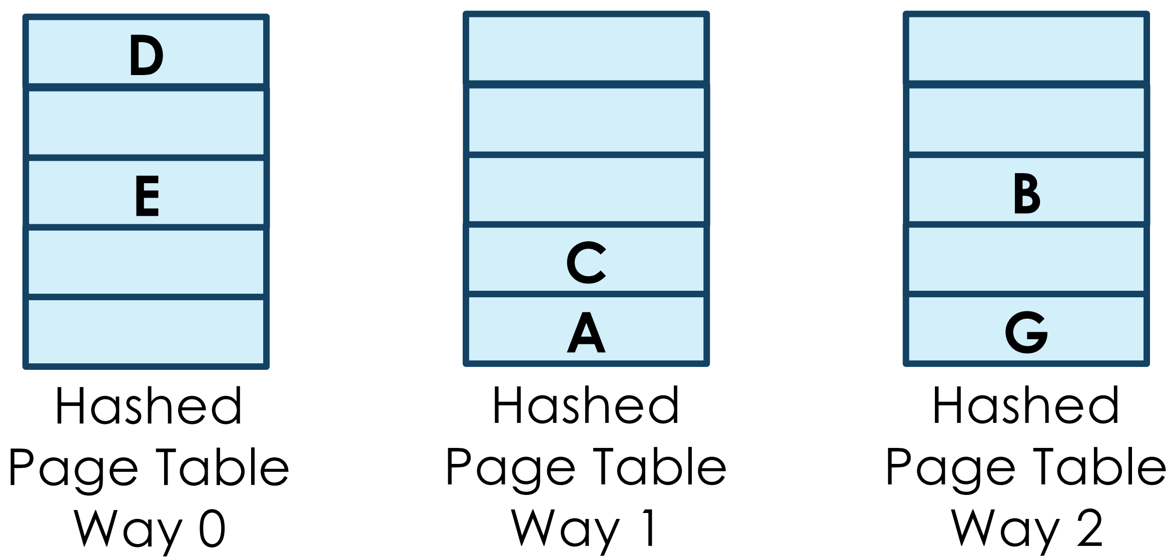


Hashed Page Tables: Recent Advances Make Them Compelling

Cuckoo Hashing

Insert G



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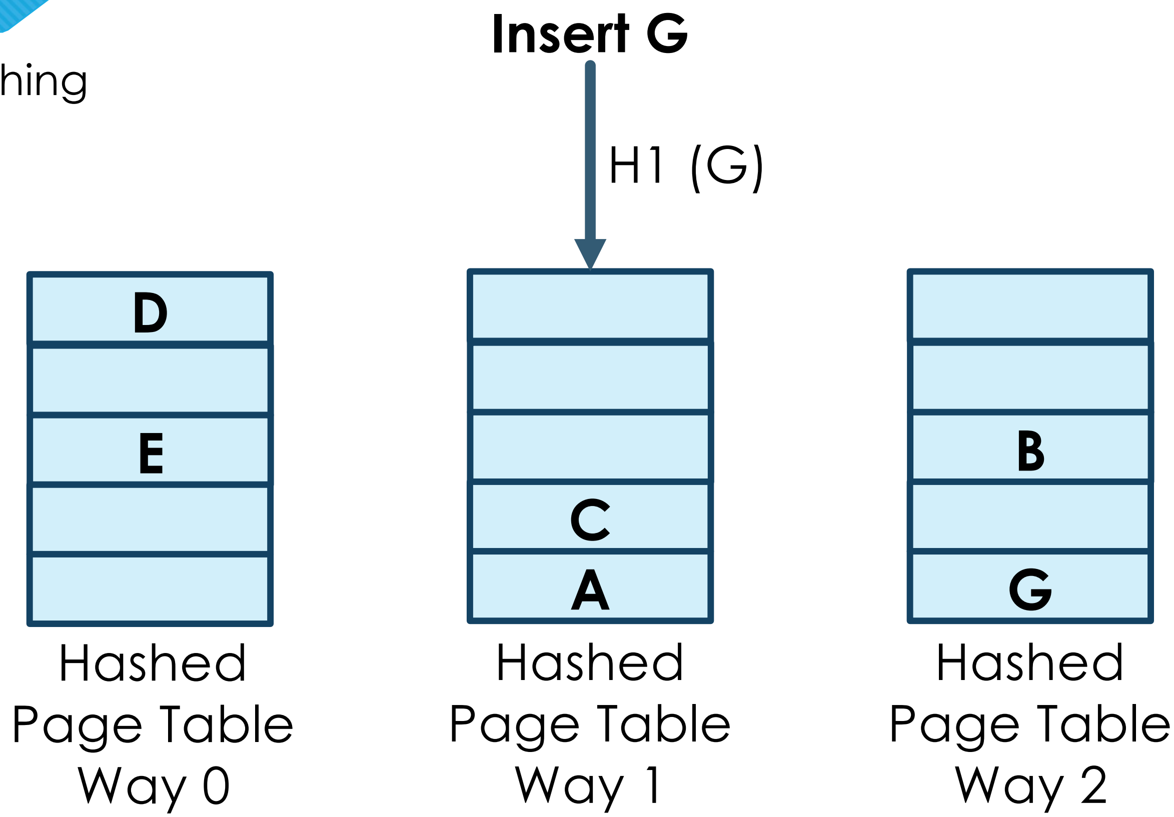

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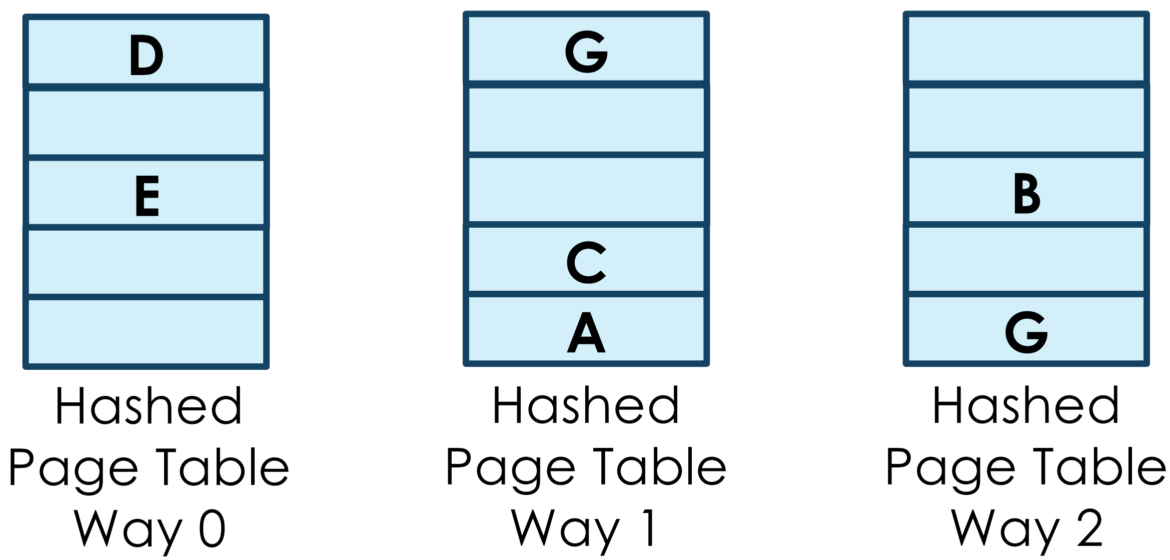
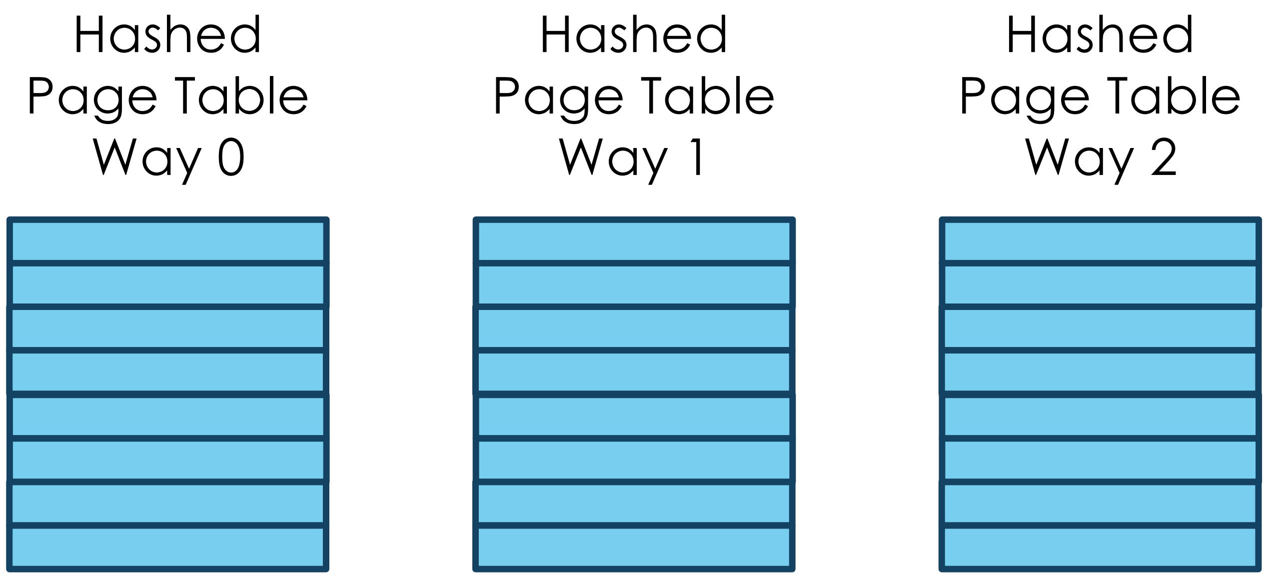


Outline of this talk

- **Problem: Contiguous Memory Requirements of Hashed Page Tables**
- ME-HPTs: Memory-Efficient Hashed Page Tables
  - ME-HPTs Design
  - ME-HPTs Key Results
- Conclusion

Hashed Page Tables: Large Contiguous Memory Chunks

- With hashed page tables – unity of allocation is one way of the page table



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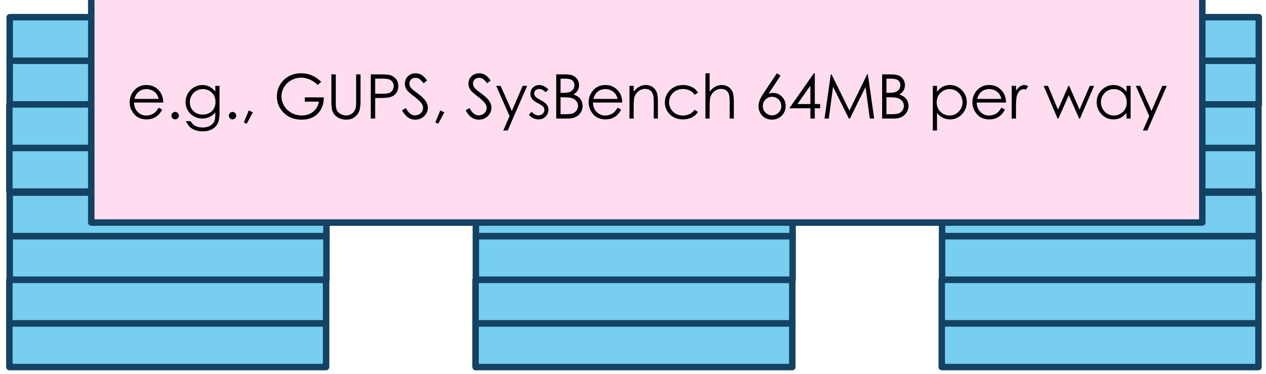
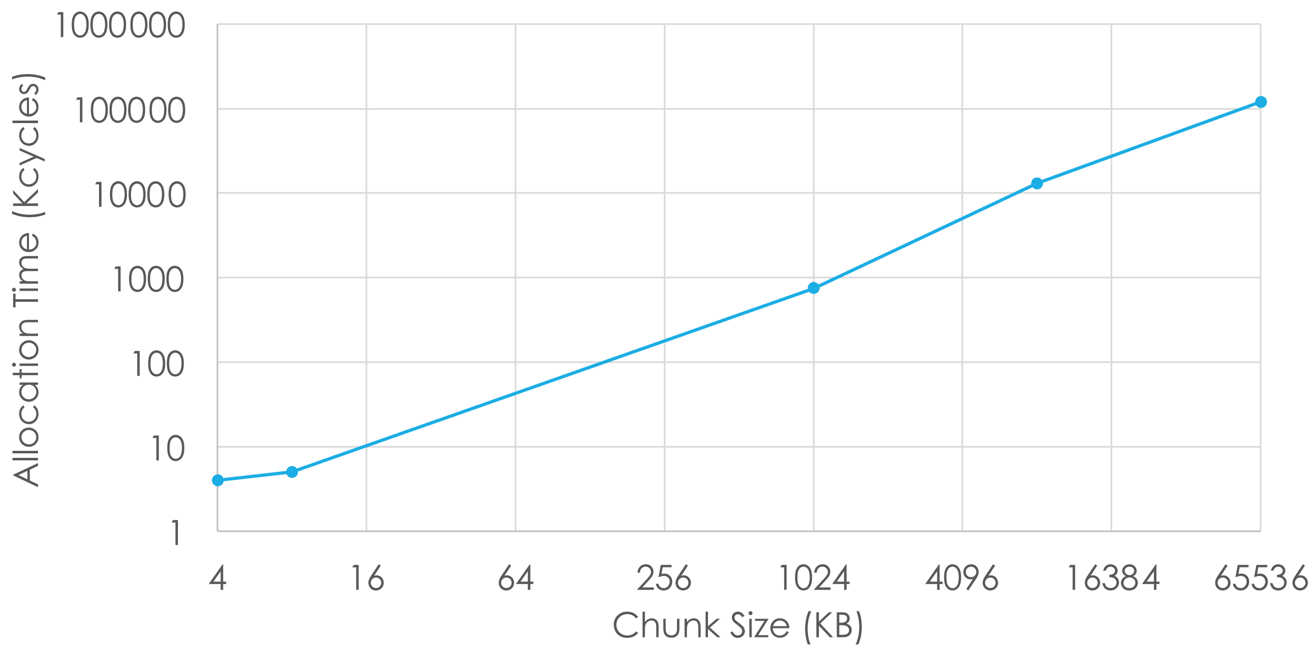


With large memory applications,
size of a way can be 10s-100s of MBs!

e.g., GUPS, SysBench 64MB per way

Hashed Page Tables: Contiguity is Expensive!

- Finding large contiguous memory chunks is expensive in busy fragmented servers



Linux server
2GHz
0.7 FMFI

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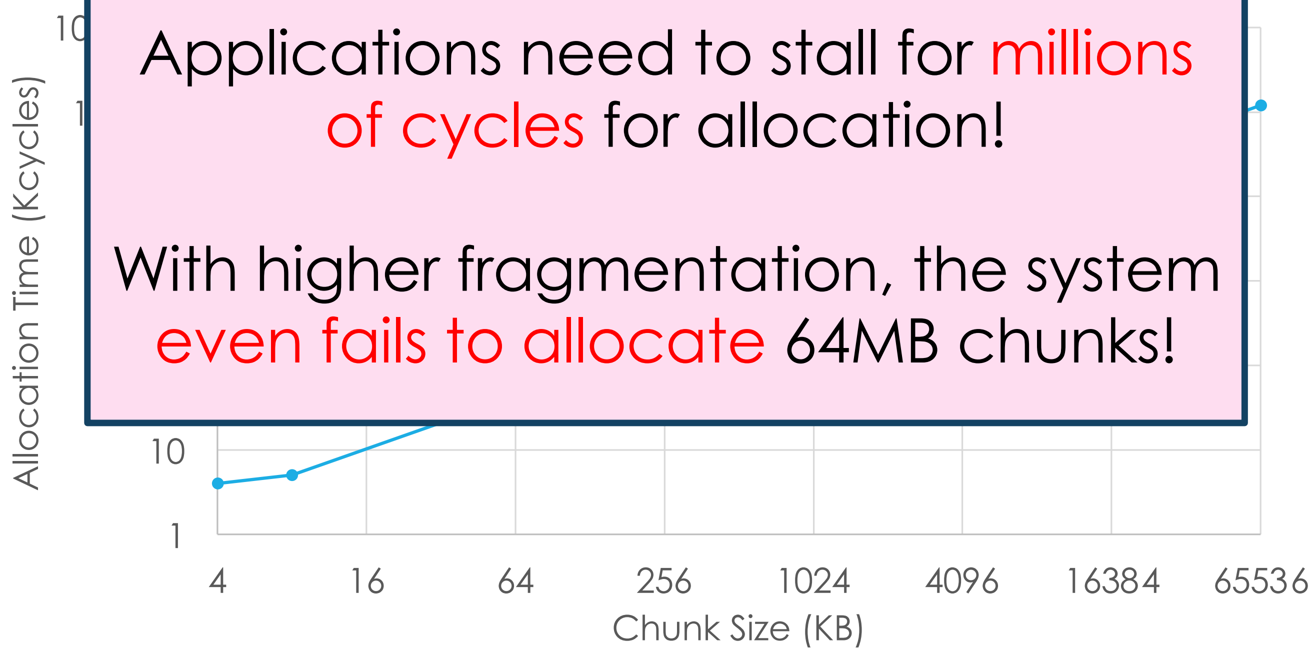

Applications need to stall for millions of cycles for allocation!

With higher fragmentation, the system even fails to allocate 64MB chunks!

Linux server
2GHz
0.7 FMFI

Contributions

- Four novel architectural techniques to provide Memory-Efficient Hashed Page Tables (**ME-HPTs**)
- Reduced memory contiguity requirement by 92%
- Sped-up applications by 9% on average
- Allow large-memory applications to run at high performance on highly fragmented servers

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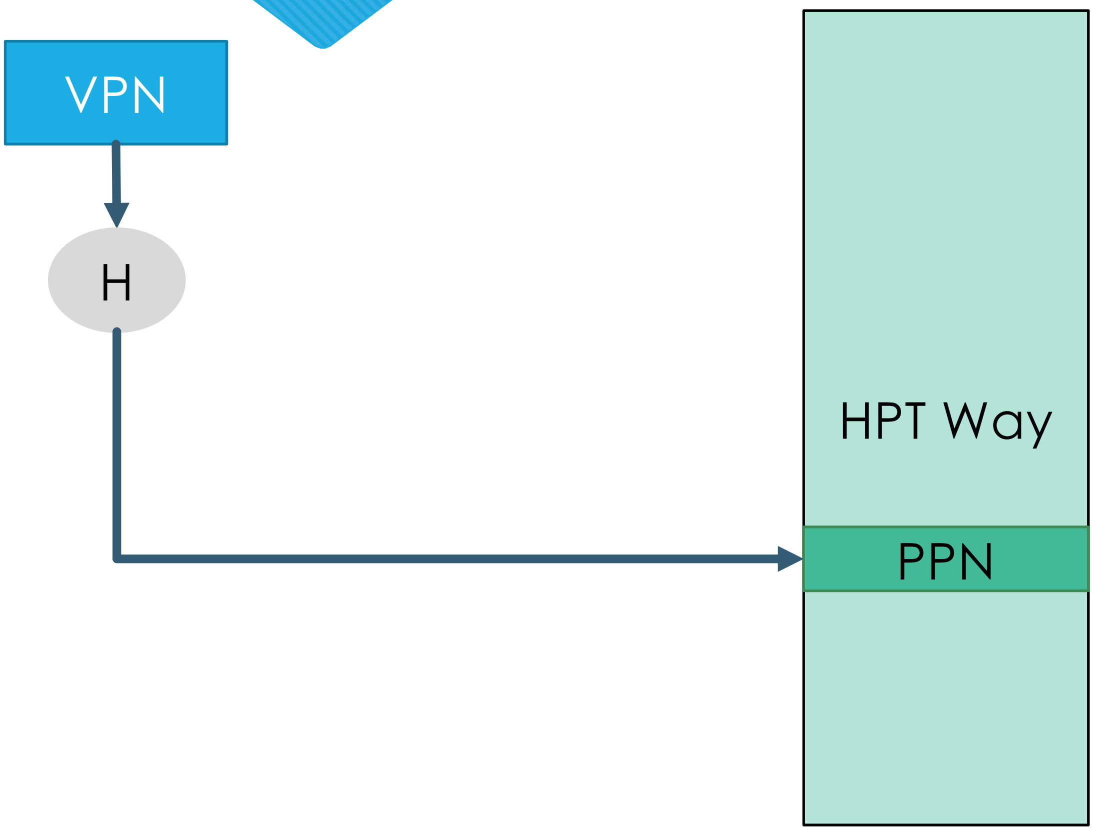
Memory-Efficient Hashed Page Tables: ME-HPTs Design Overview

- Memory-Efficient Hashed Page Tables (ME-HPTs): Four novel architectural techniques
- Directly minimizing contiguity requirements
  - Logical-to-Physical (L2P) Table
  - Dynamically Changing Chunk Size
- Indirectly minimizing contiguity requirements by minimizing memory consumption
  - In-place Page Table Resizing
  - Per-way Page Table Resizing

Memory Efficient Hashed Page Tables: Logical-to-Physical (L2P) Table



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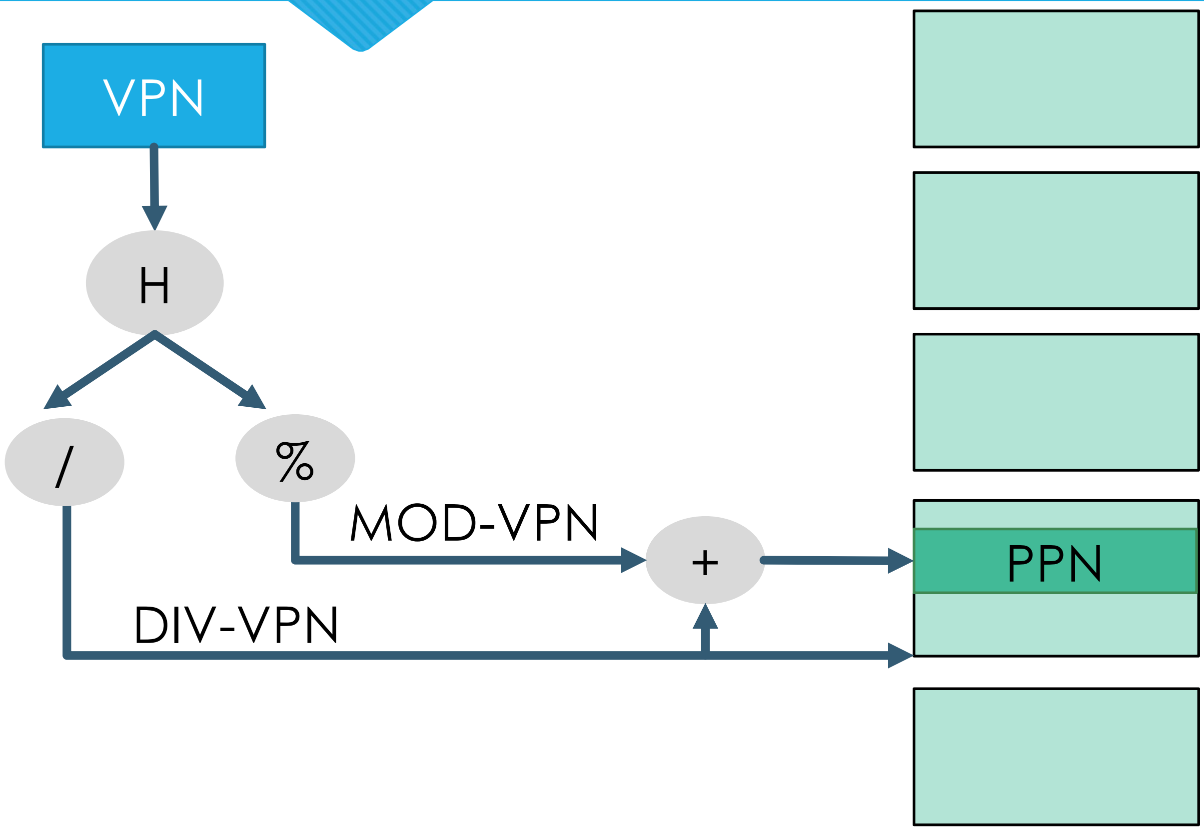

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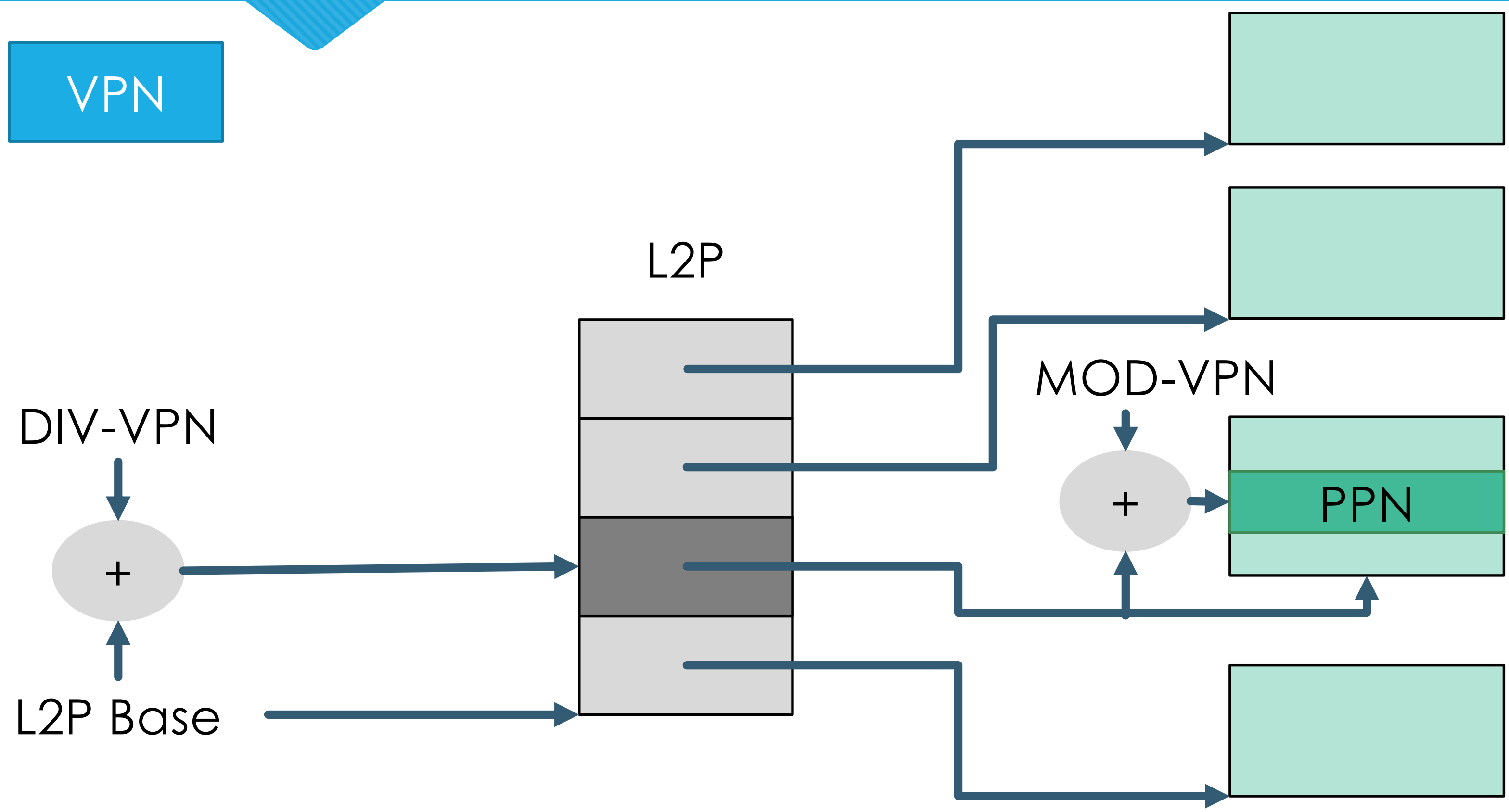
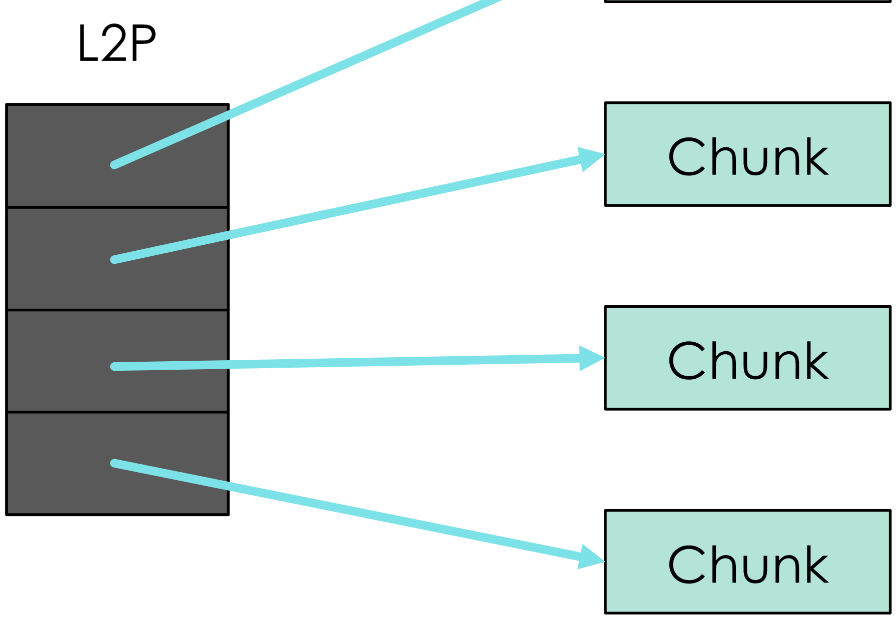
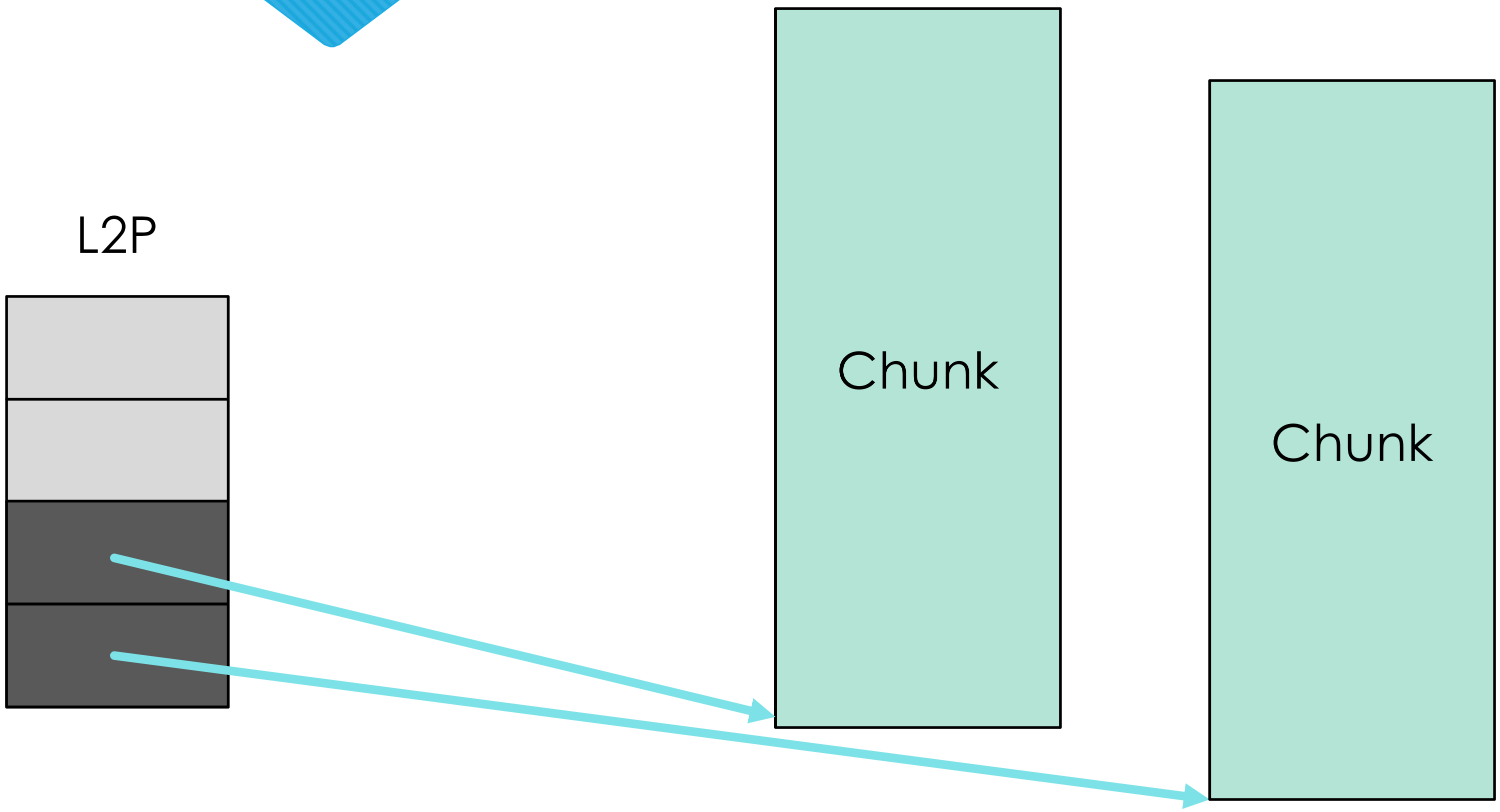


Memory Efficient Hashed Page Tables: Dynamically Changing Chunk Sizes



L2P is fixed in size!
What if the application needs more memory?

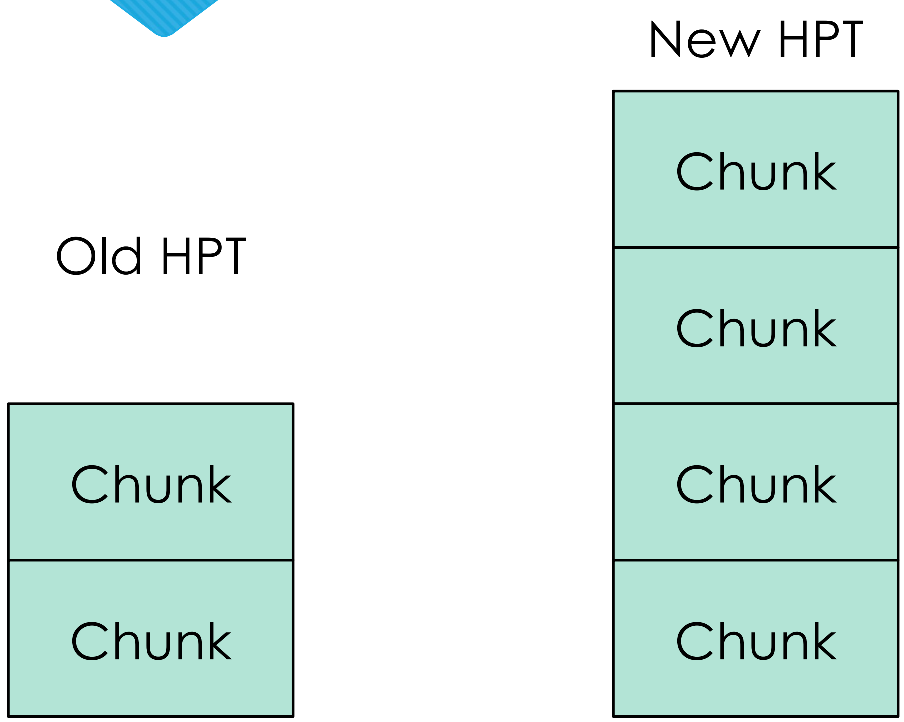
Memory Efficient Hashed Page Tables: Dynamically Changing Chunk Sizes



Memory Efficient Hashed Page Tables: Design Overview

- ME-HPTs: Four novel architectural techniques
- Directly minimizing contiguity requirements
  - Logical-to-Physical (L2P) Table
  - Dynamically Changing Chunk Size
- **Indirectly minimizing contiguity requirements by minimizing memory consumption**
  - **In-place Page Table Resizing**
  - **Per-way Page Table Resizing**

Baseline Page Table Resizing



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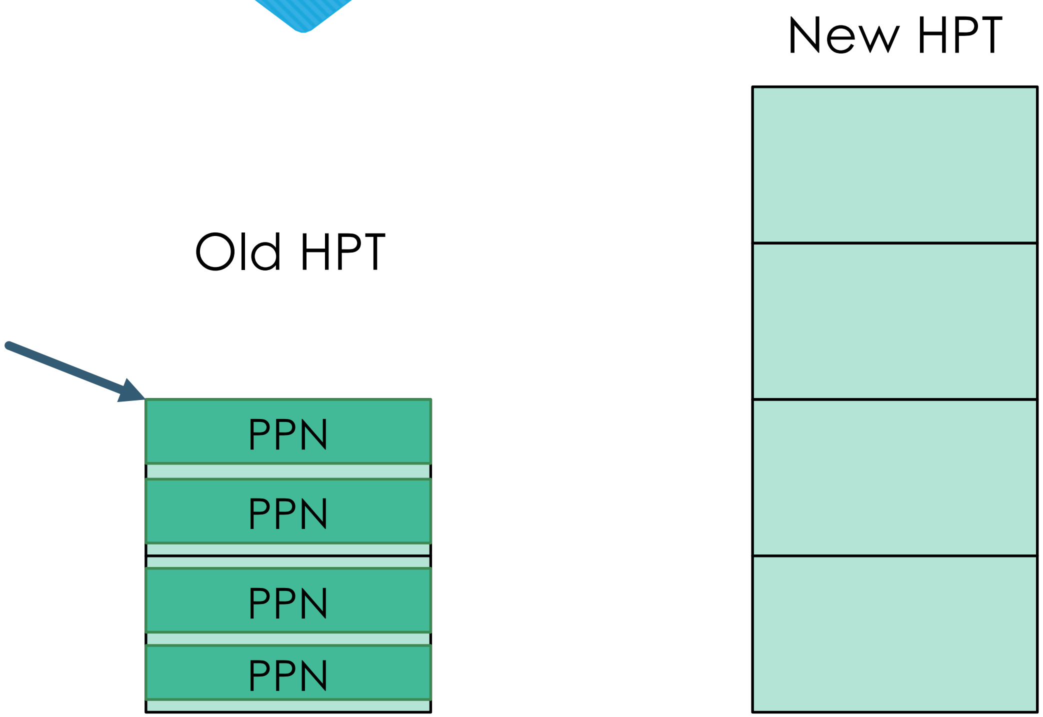

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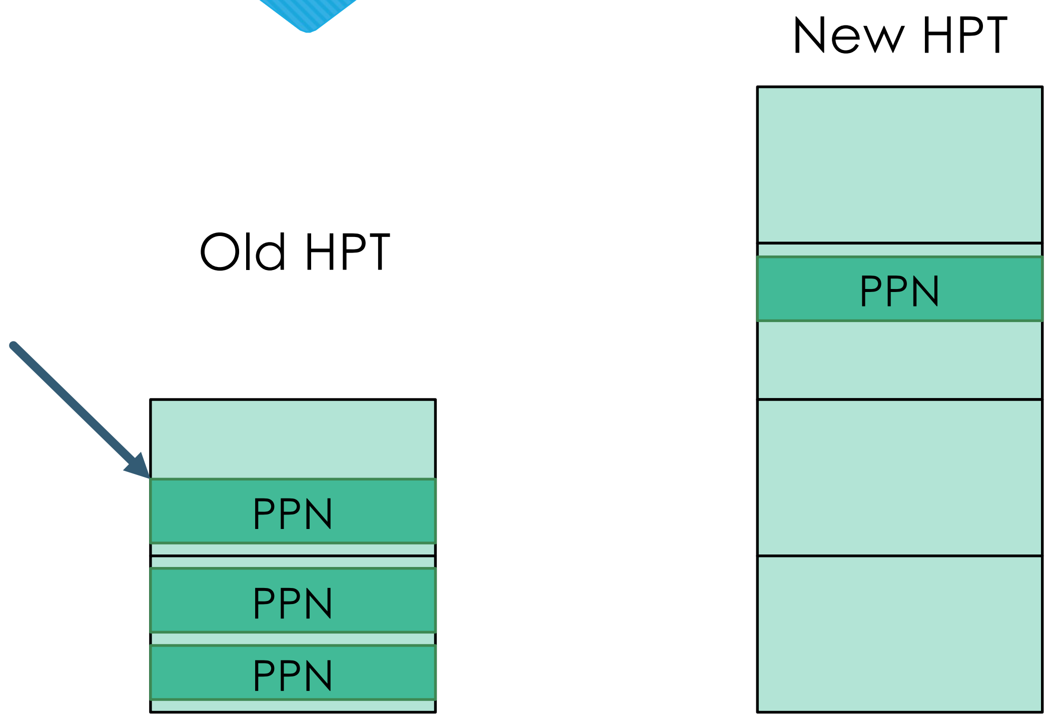

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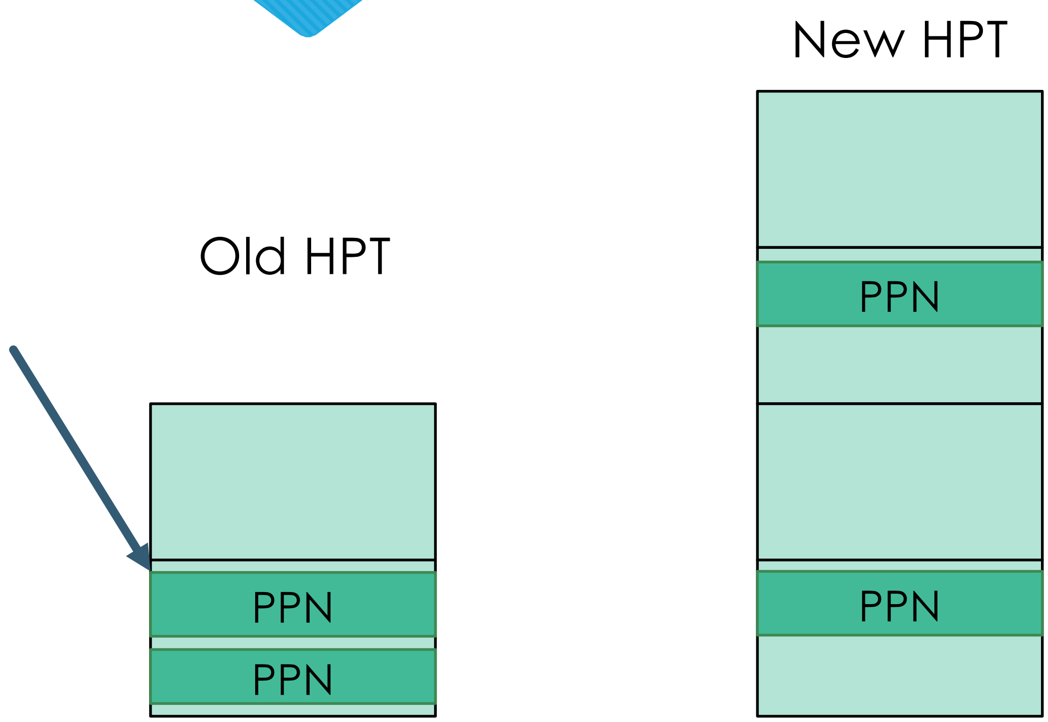

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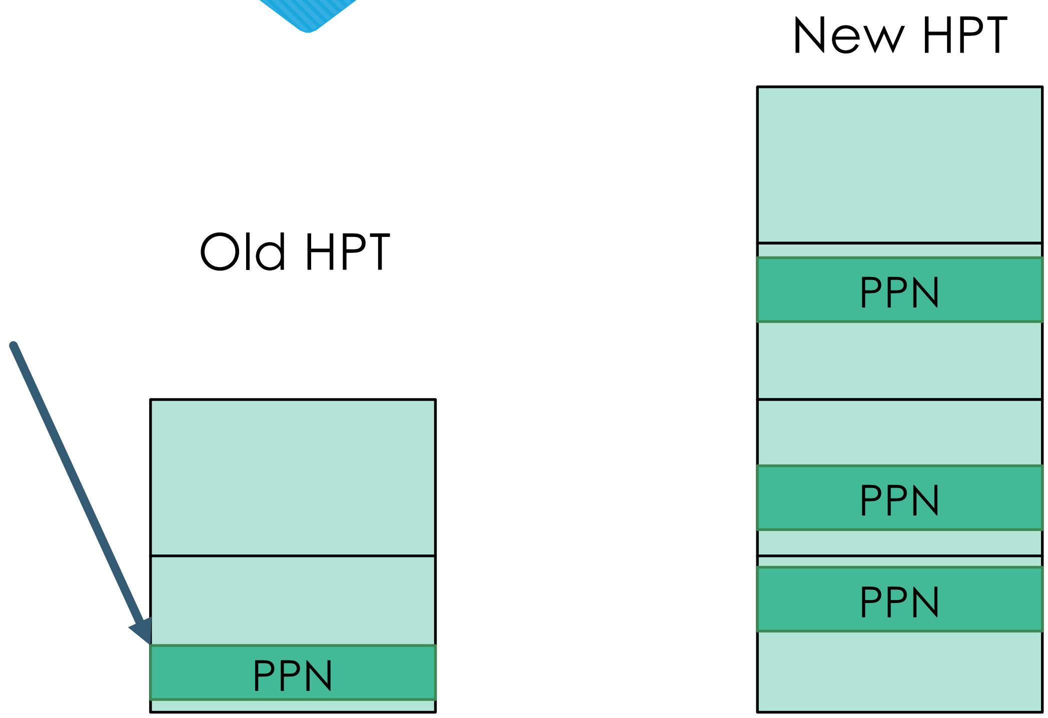

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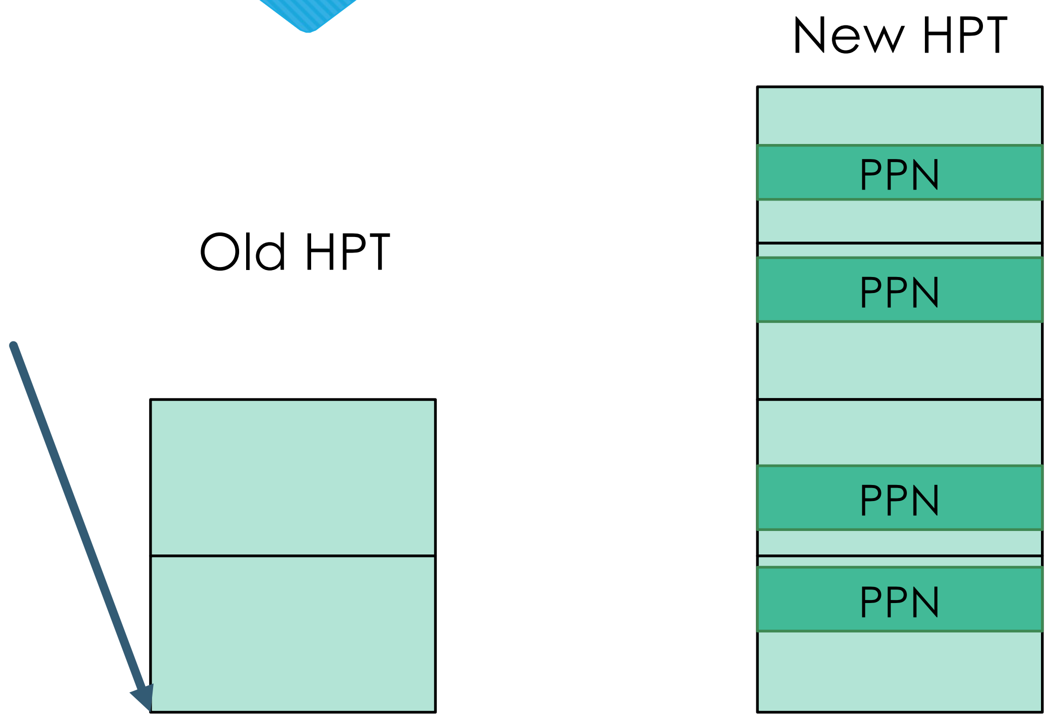

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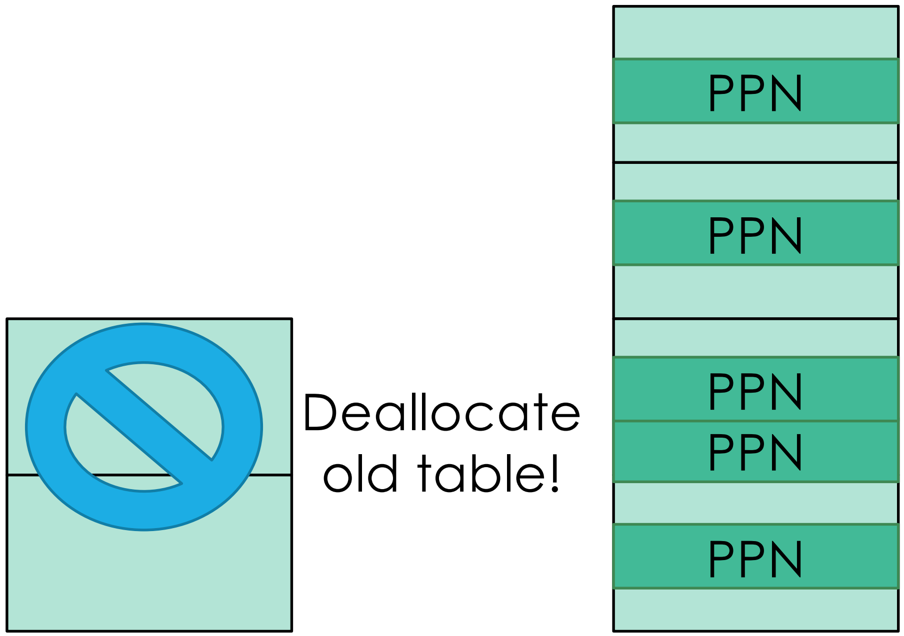
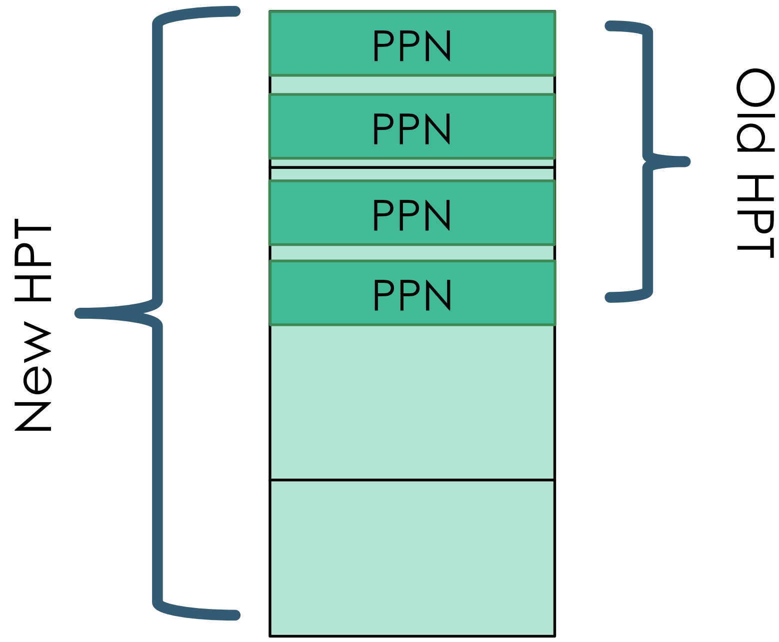


Until the old table is deallocated, we keep **both tables** in memory!

Memory Efficient Hashed Page Tables: In-Place Page Table Resizing

- Keep both tables in shared memory space
- Same hash function for both tables
- On rehash, some entries stay in the same chunk, others move to new chunks



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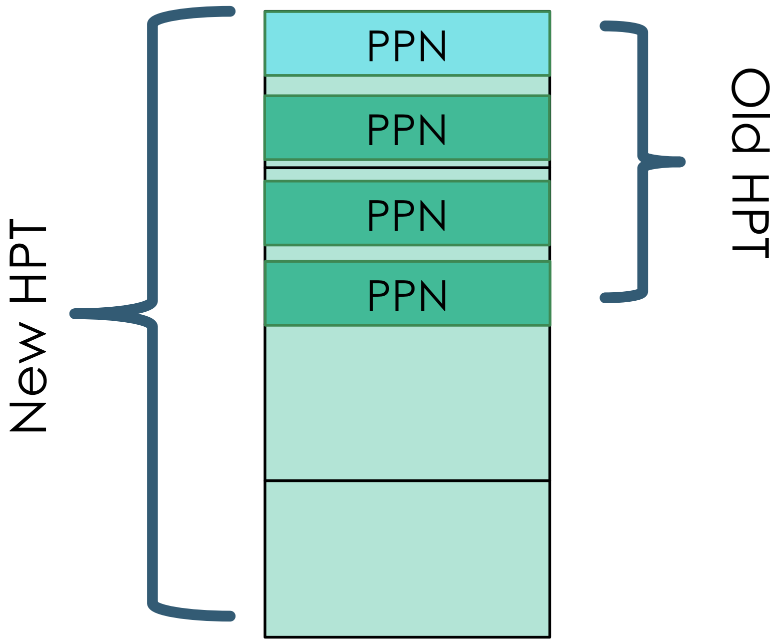

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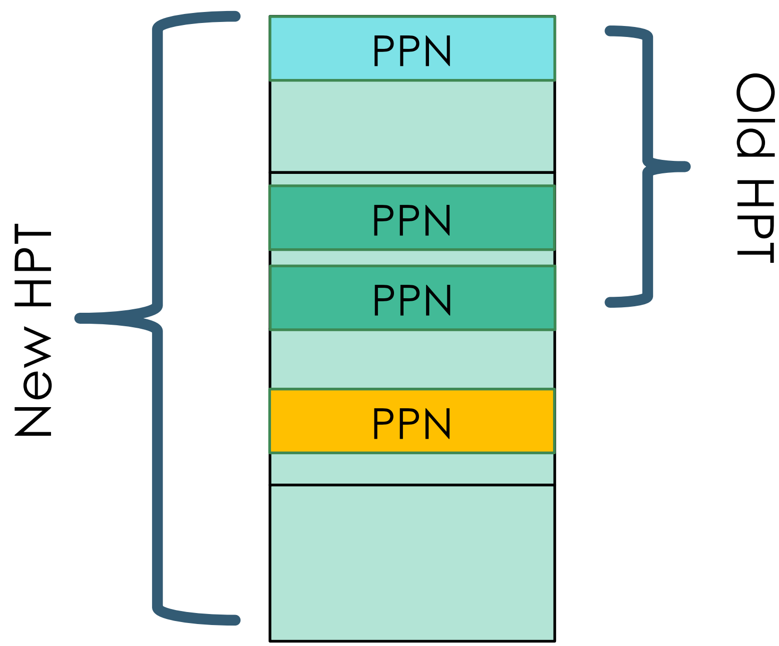

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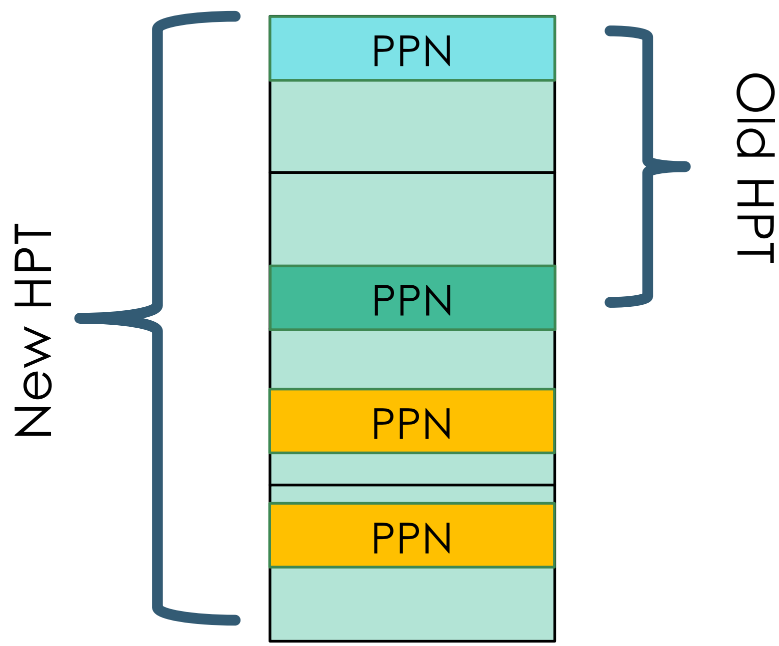

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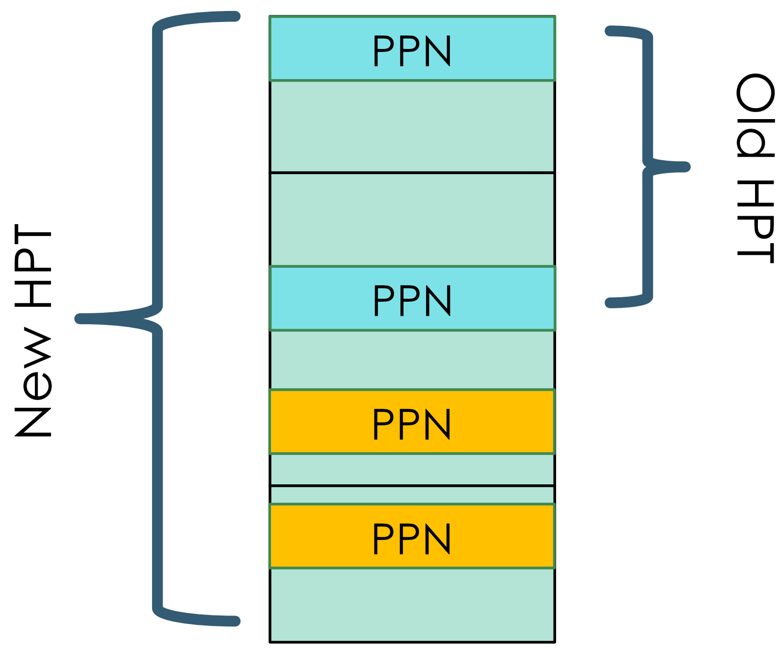

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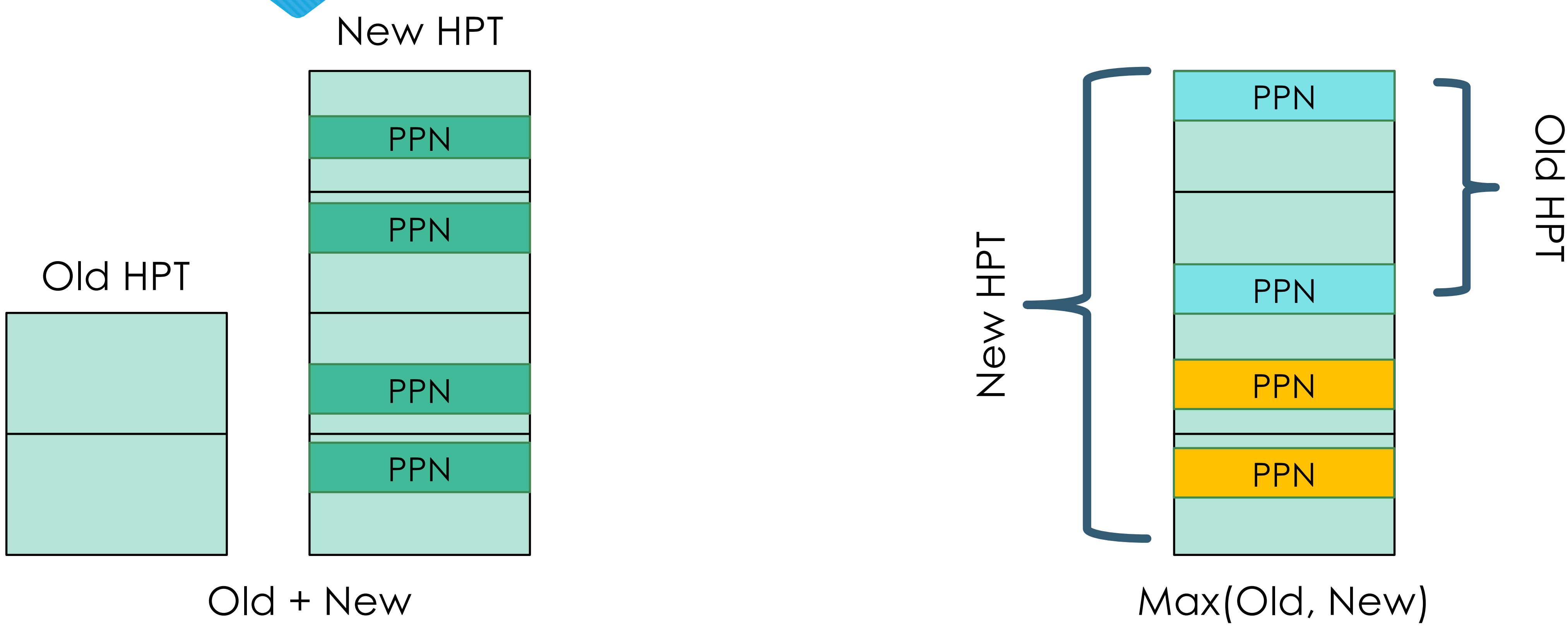
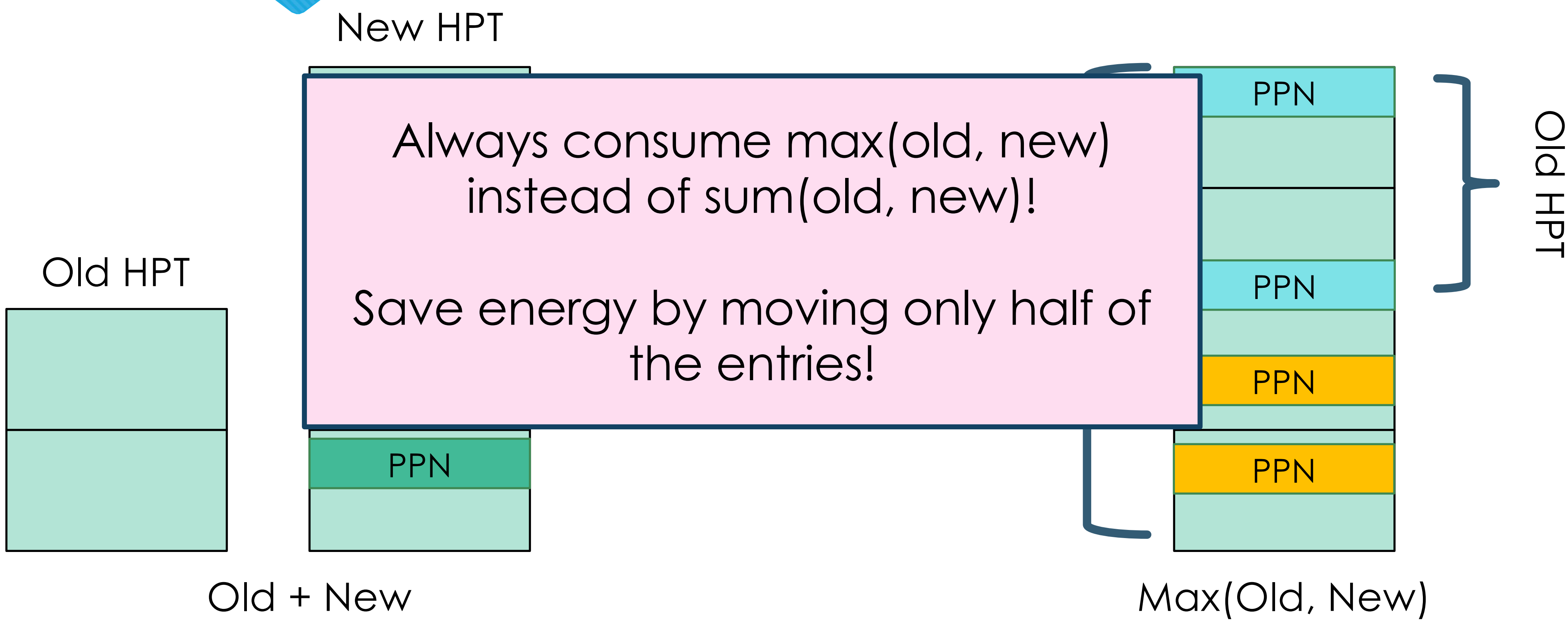


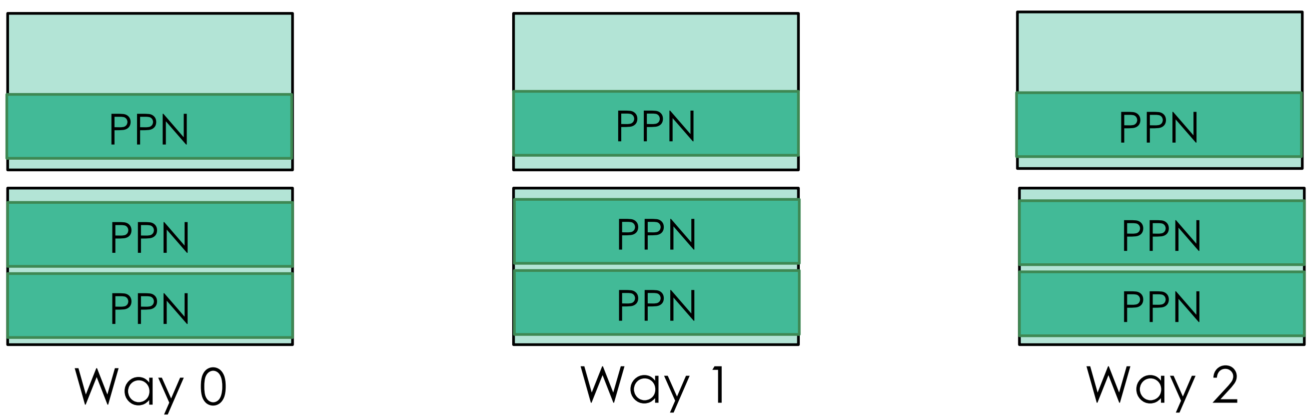
Memory Efficient Hashed Page Tables: In-Place Page Table Resizing

Always consume max(old, new) instead of sum(old, new)!

Save energy by moving only half of the entries!



Baseline Page Table Resizing



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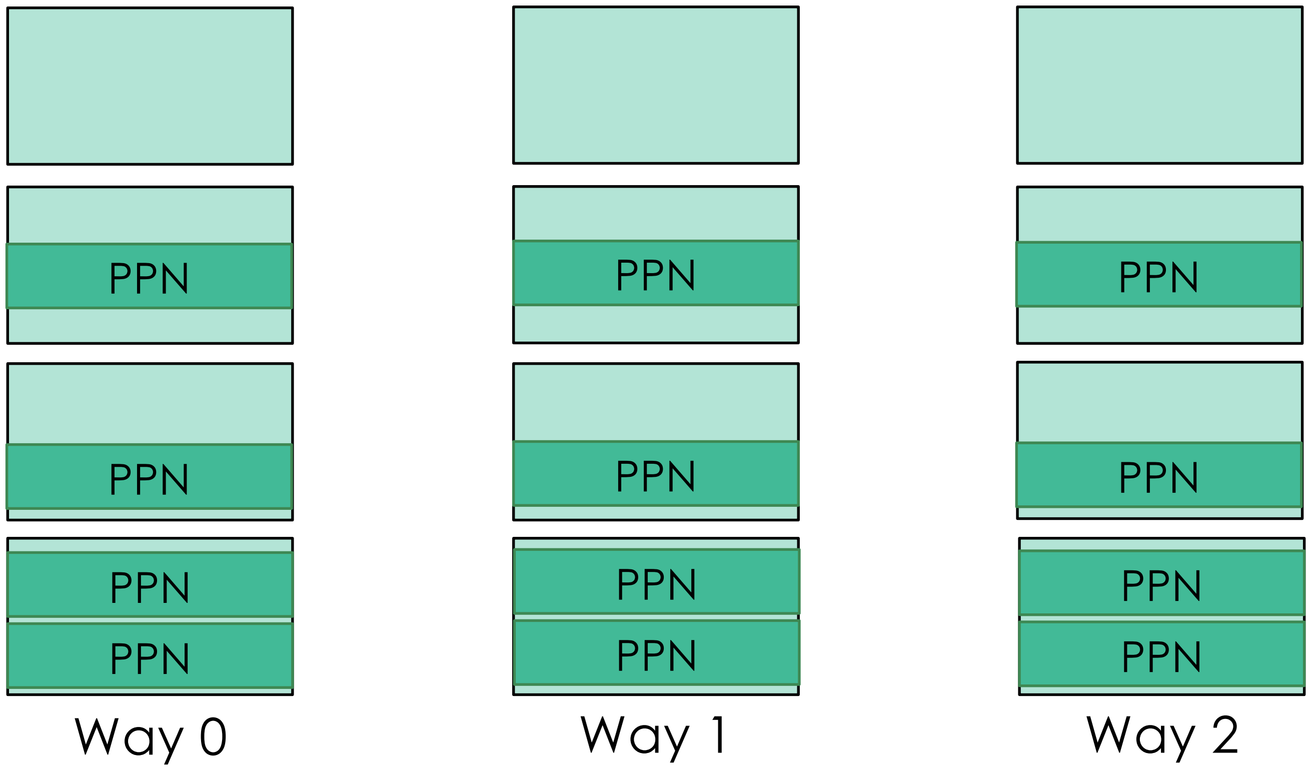
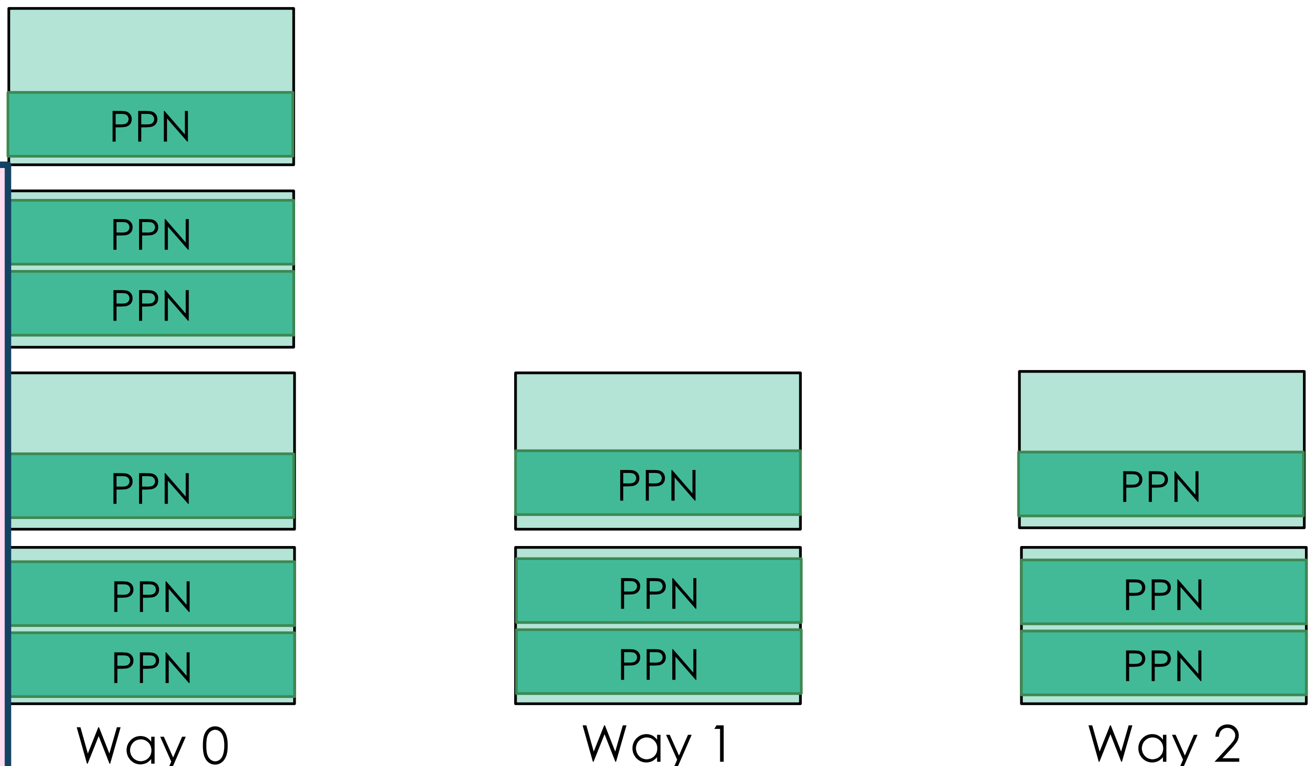


Often memory underutilized!

Memory Efficient Hashed Page Tables: Per Way Page Table Resizing

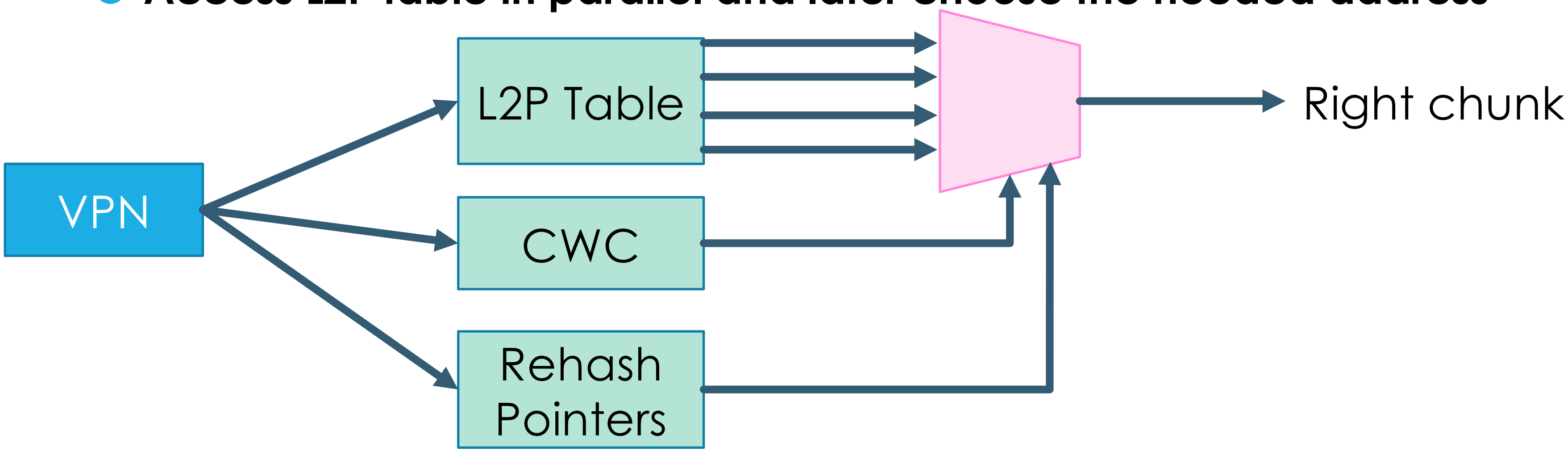
Memory much better utilized!

Need to care: where to insert new element and which way to upsize!



ME-HPTs Implementation:
Hiding the L2P Table Access Latency

- Elastic Cuckoo Page Tables (ECPTs) use
  - Cuckoo walk caches (CWCs) to prune the number of parallel requests
  - Rehash Pointers to decide if a new or old HPT needs to accessed
- **Access L2P table in parallel and later choose the needed address**



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- Page Table Organizations
- Hashed Page Tables Memory Requirements
- **ME-HPTs: Memory-Efficient Hashed Page Tables**
  - ME-HPTs Design
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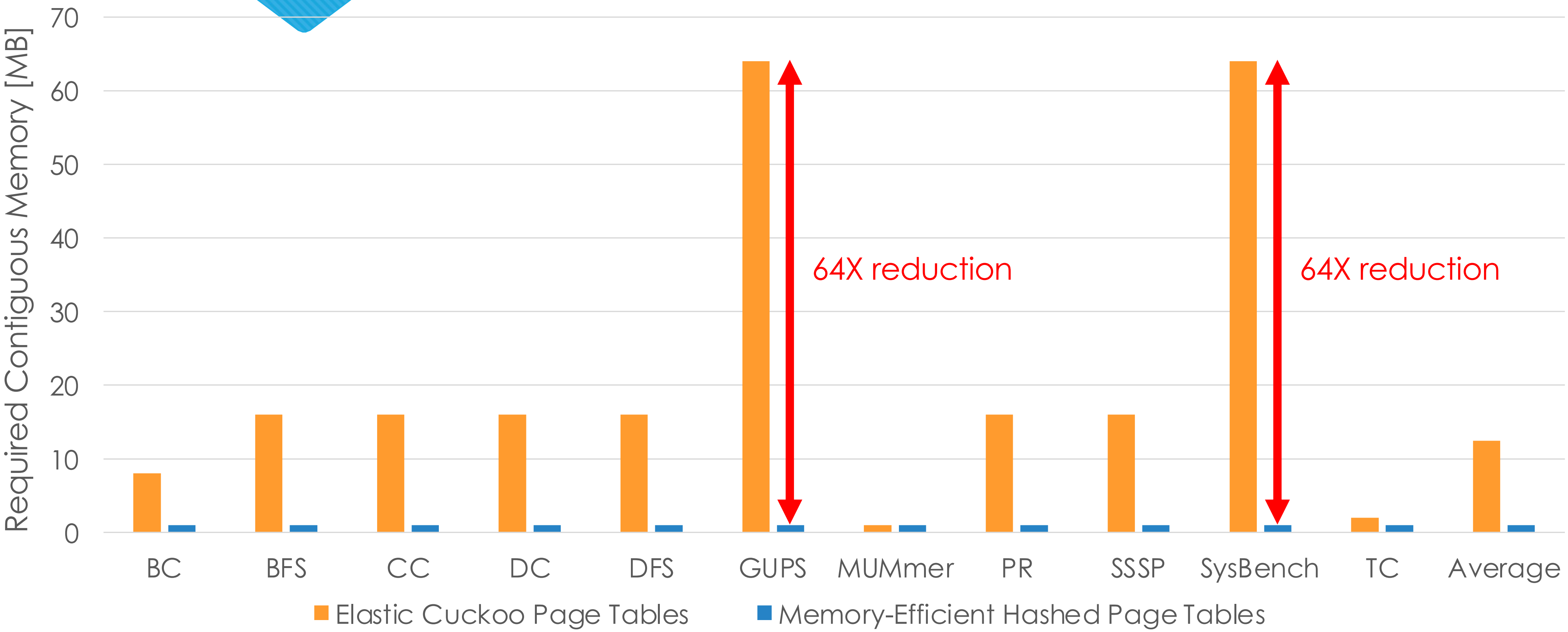
Significant Memory Contiguity Savings



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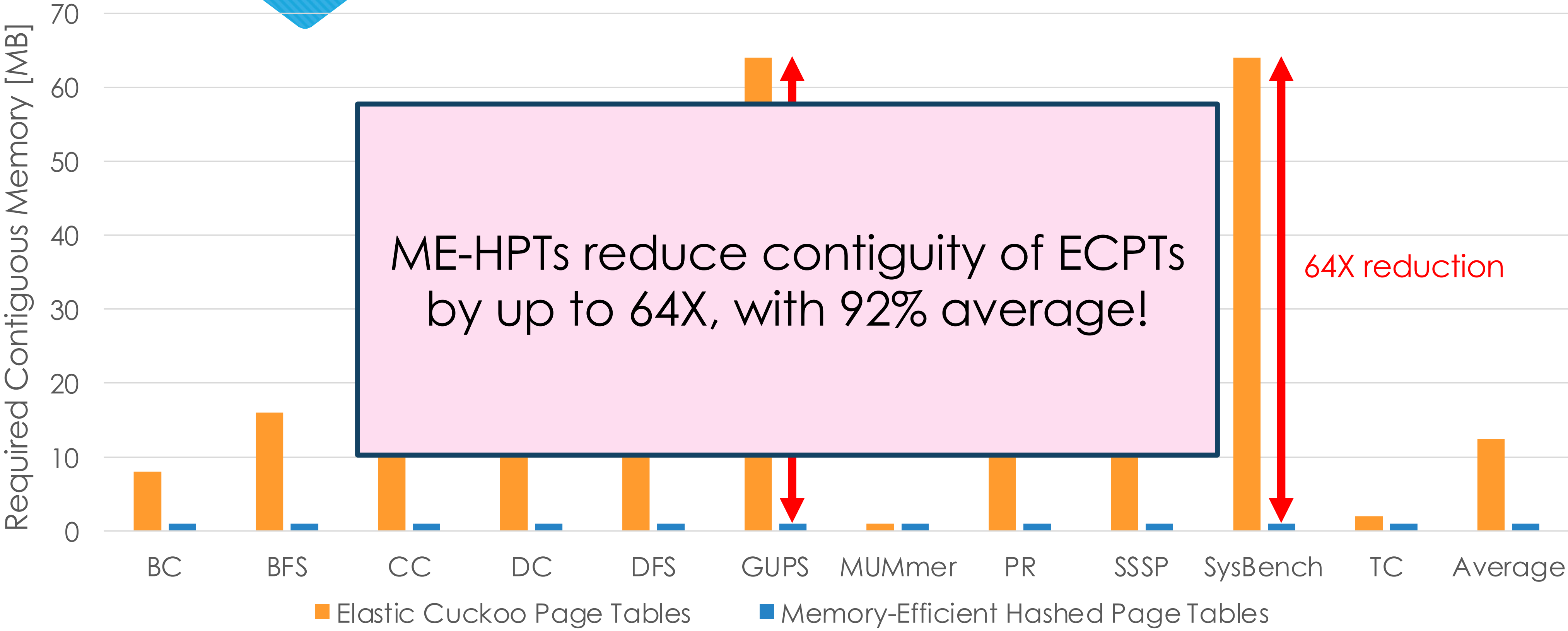
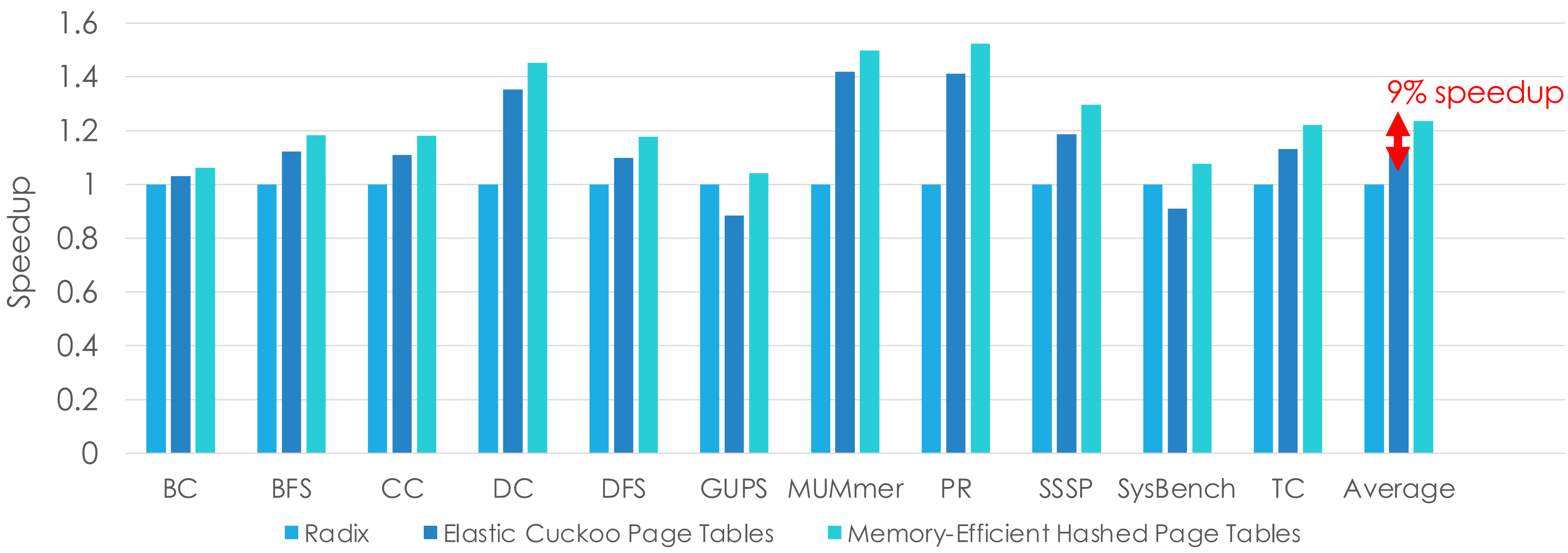


ME-HPTs reduce contiguity of ECPTs by up to 64X, with 92% average!

Improved Application Performance



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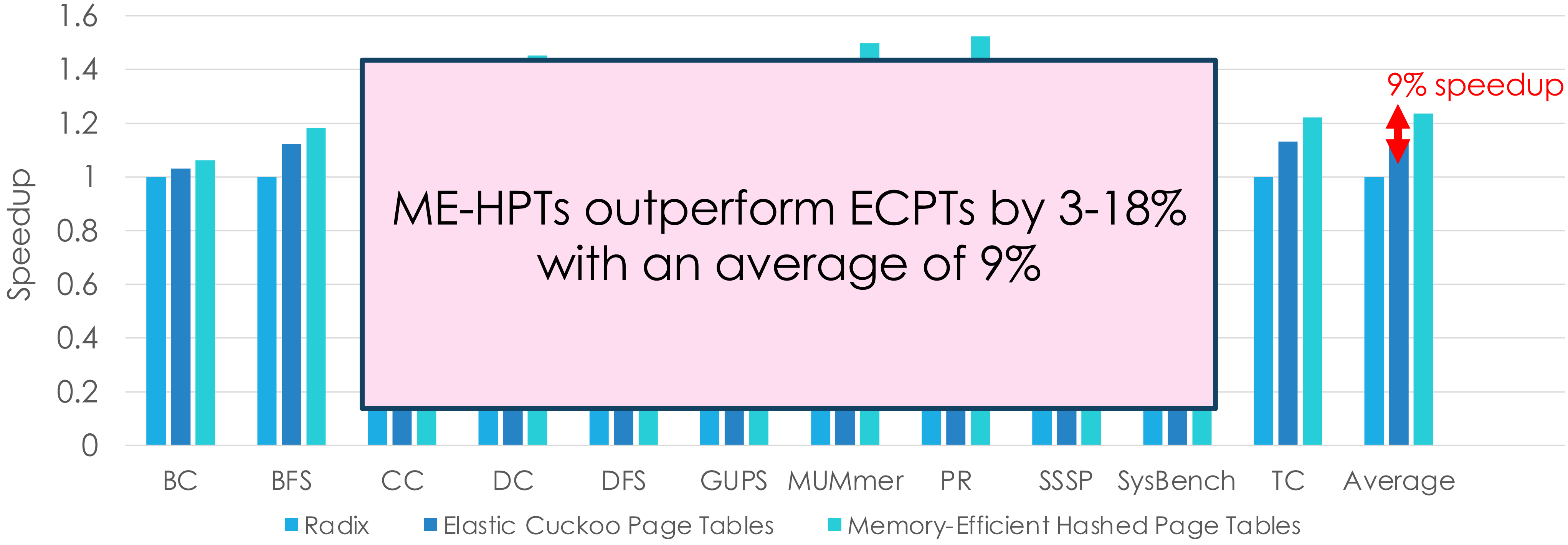

Conclusion

- Four novel architectural techniques to provide Memory-Efficient Hashed Page Tables
  - L2P Table
  - Dynamically Changing Chunk Sizes
  - In-Place Page Table Resizing
  - Per-Way Page Table Resizing
- Reduced memory contiguity requirement by 92%
- Sped-up applications by 9% on average
- Allow large-memory applications to run at high performance on highly fragmented servers

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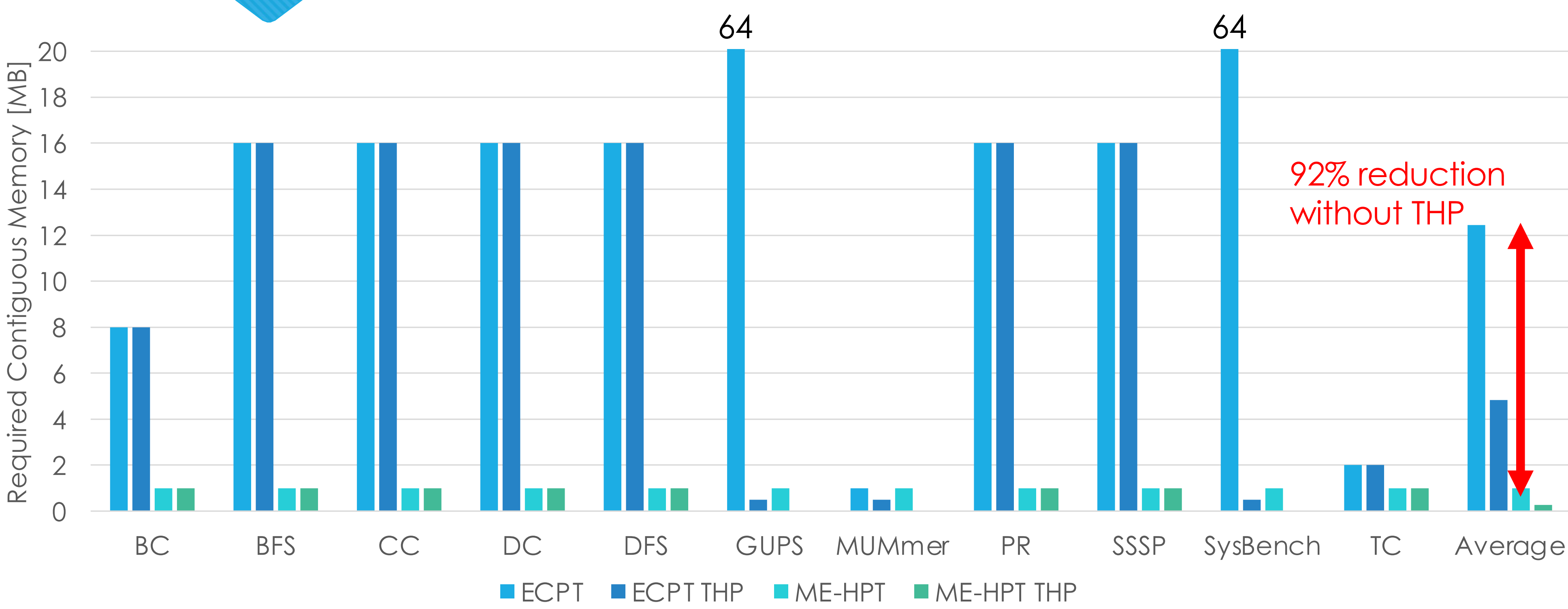
ME-HPTs Key Results: Significant Memory Contiguity Savings



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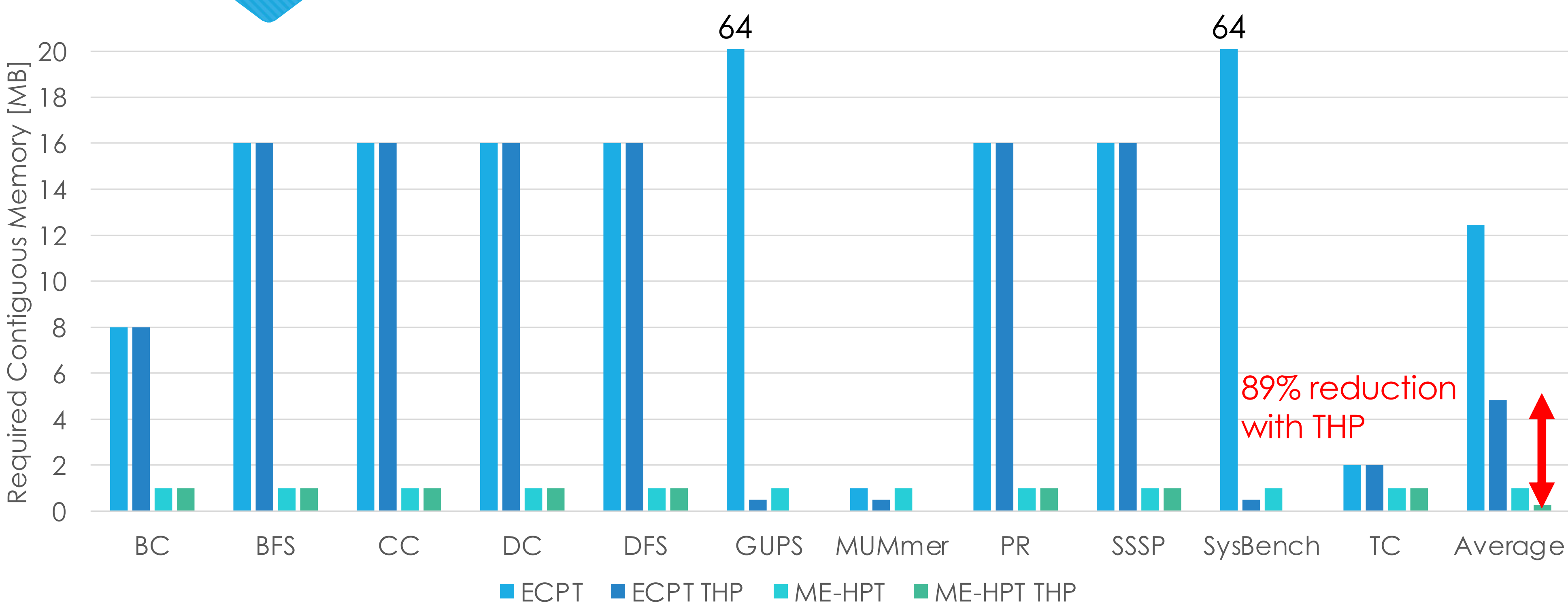

ME-HPTs Key Results: Memory Consumption Reduction

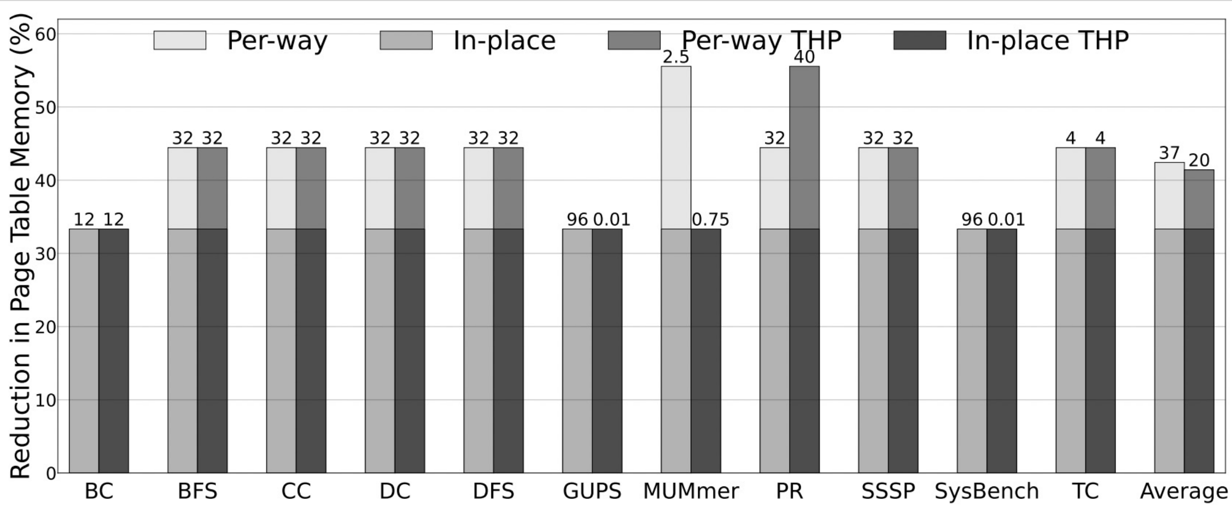

Fig. 10: Reduction in page table memory attained by ME-HPT over the ECPT baseline. The number on top of each bar is the absolute reduction in Mbytes.

ME-HPTs Key Results:
Number of L2P Table Entries Used per App

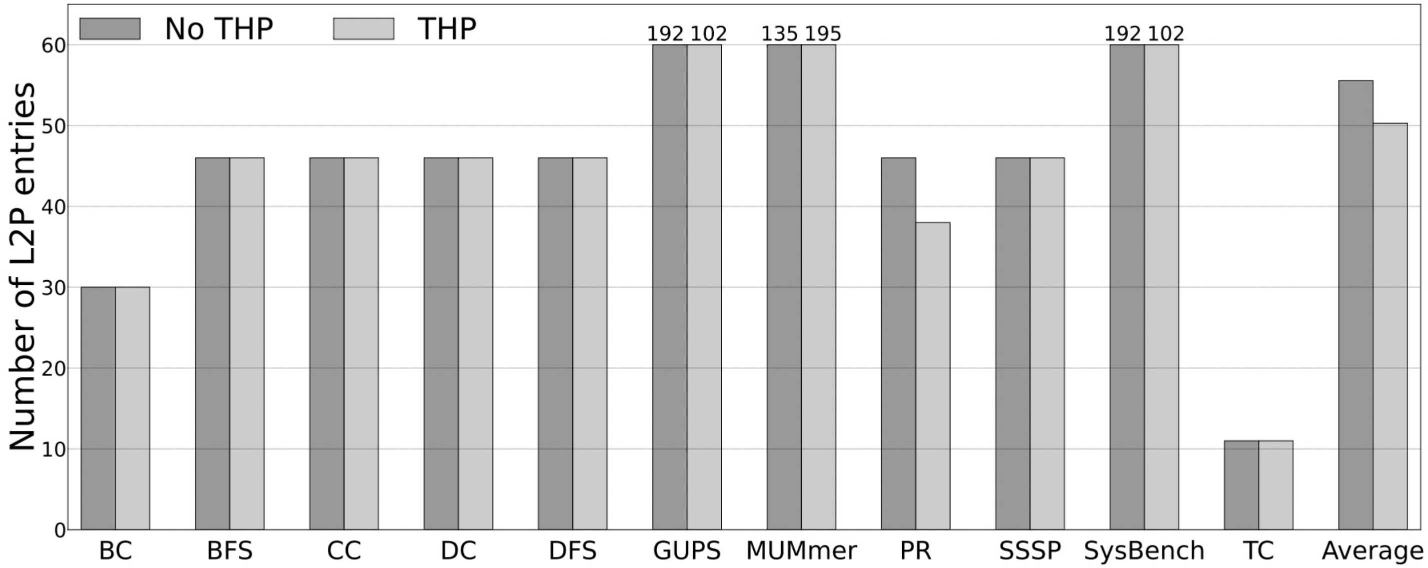

Fig. 14: Number of L2P table entries used per application.

ME-HPTs Other Use Cases

- Techniques applicable to various hash table designs beyond HPTs
- **Scalable Secure Directories**
  - Directories as set-associative structures
  - Efficient resizing required
- **Memory Indexing**
  - Hash tables commonly used to implement memory indices of databases, file systems…
  - Dynamic resizing key operation: in-place resizing useful
- **Key-value Stores**
  - Dynamic structures whose size is unknown ahead of time