Rethinking Address Translation in the Age of Containers, Serverless Computing, and Non-Volatile Memory

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ARM Research Summit
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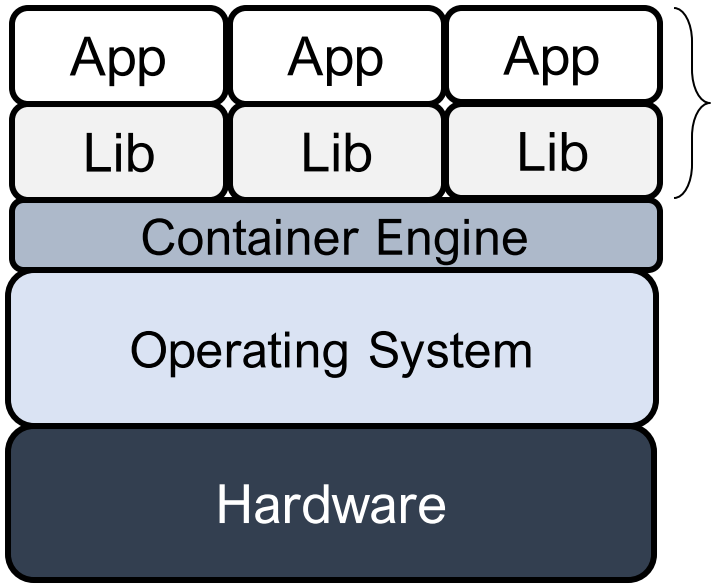
ILLINOIS

New Era in Cloud Computing: Containers

1. Lightweight
2. Faster bring-up
3. Higher consolidation

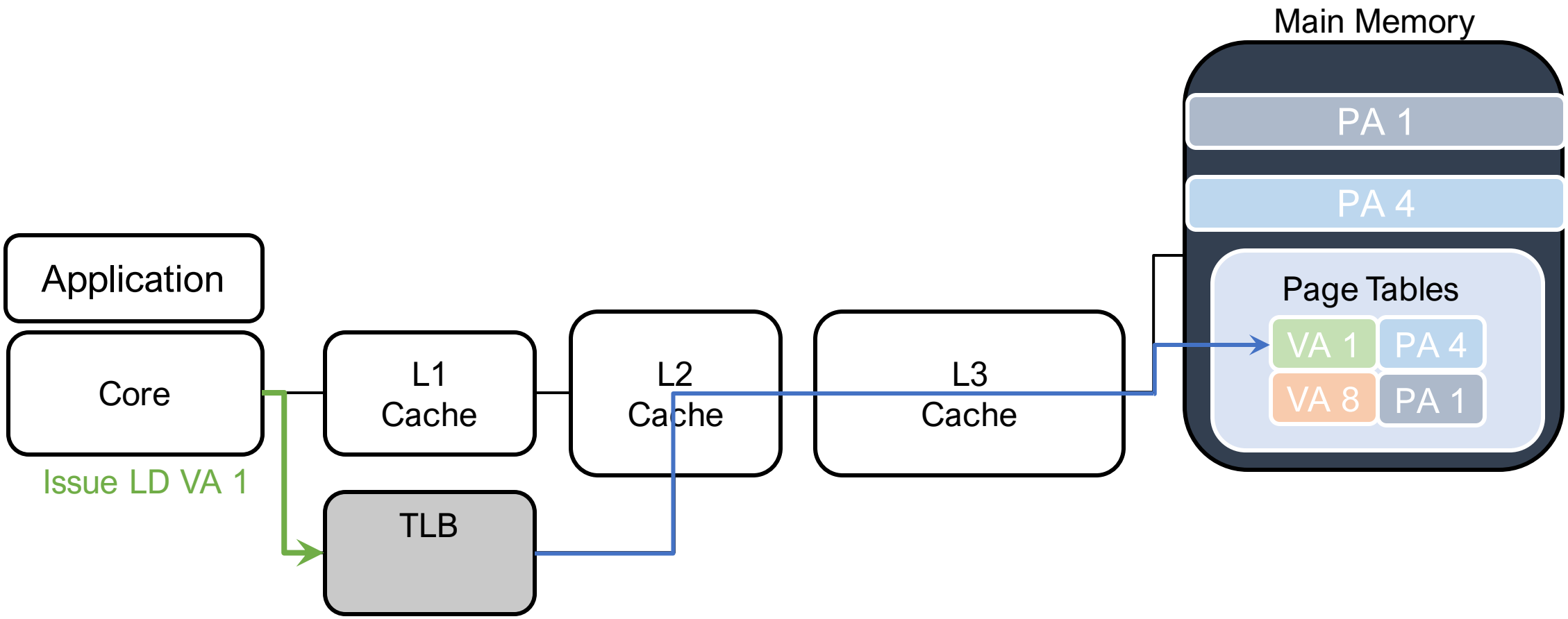


Containers

High number of containers

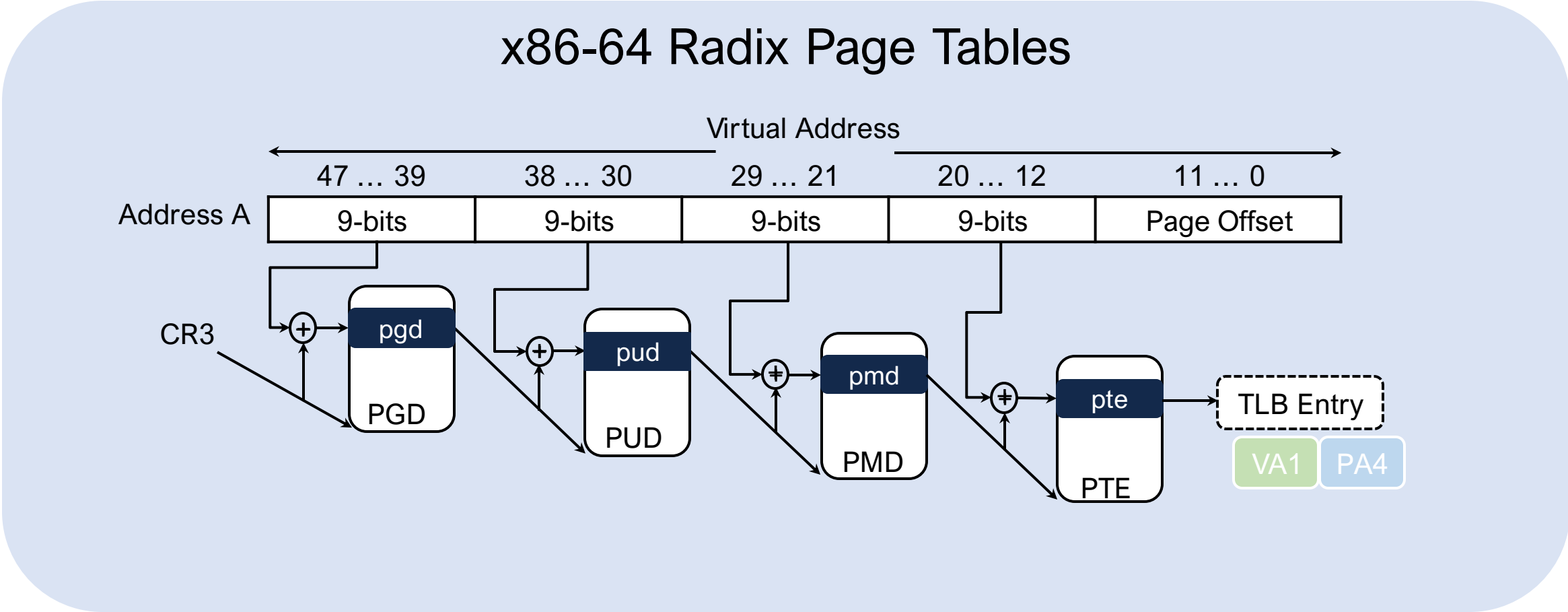
Very frequent context switches

Address Translation System

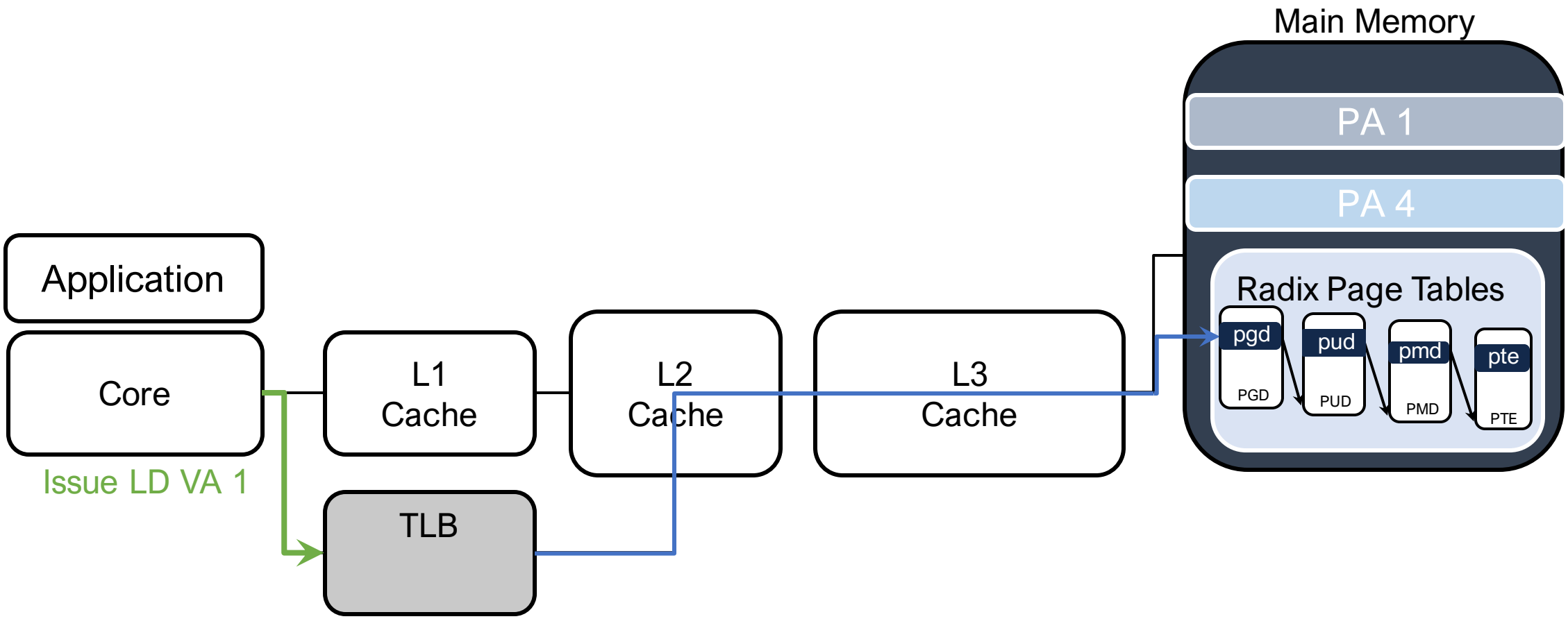


TLB Miss → "Page Walk" = Fetch entry from page table

Address Translation System

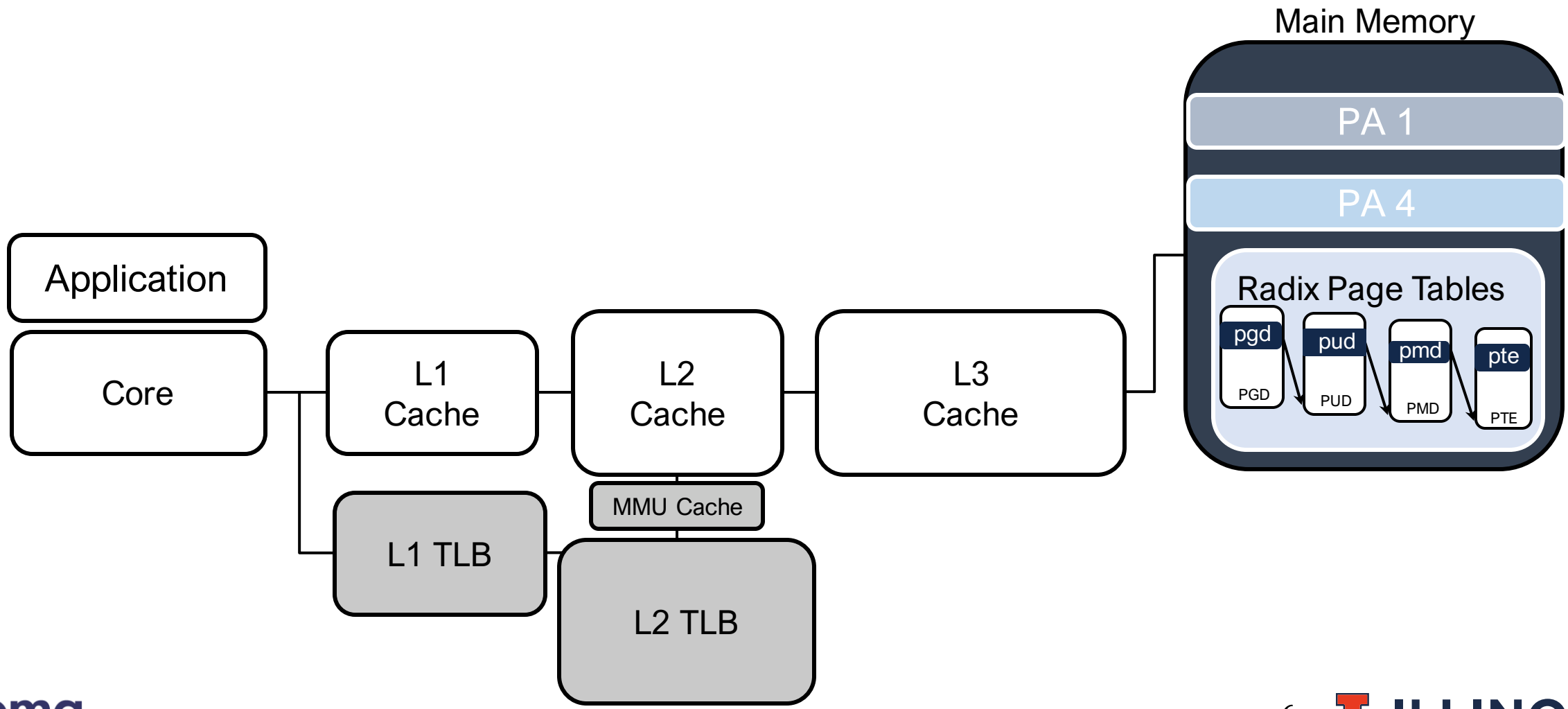


Address Translation System



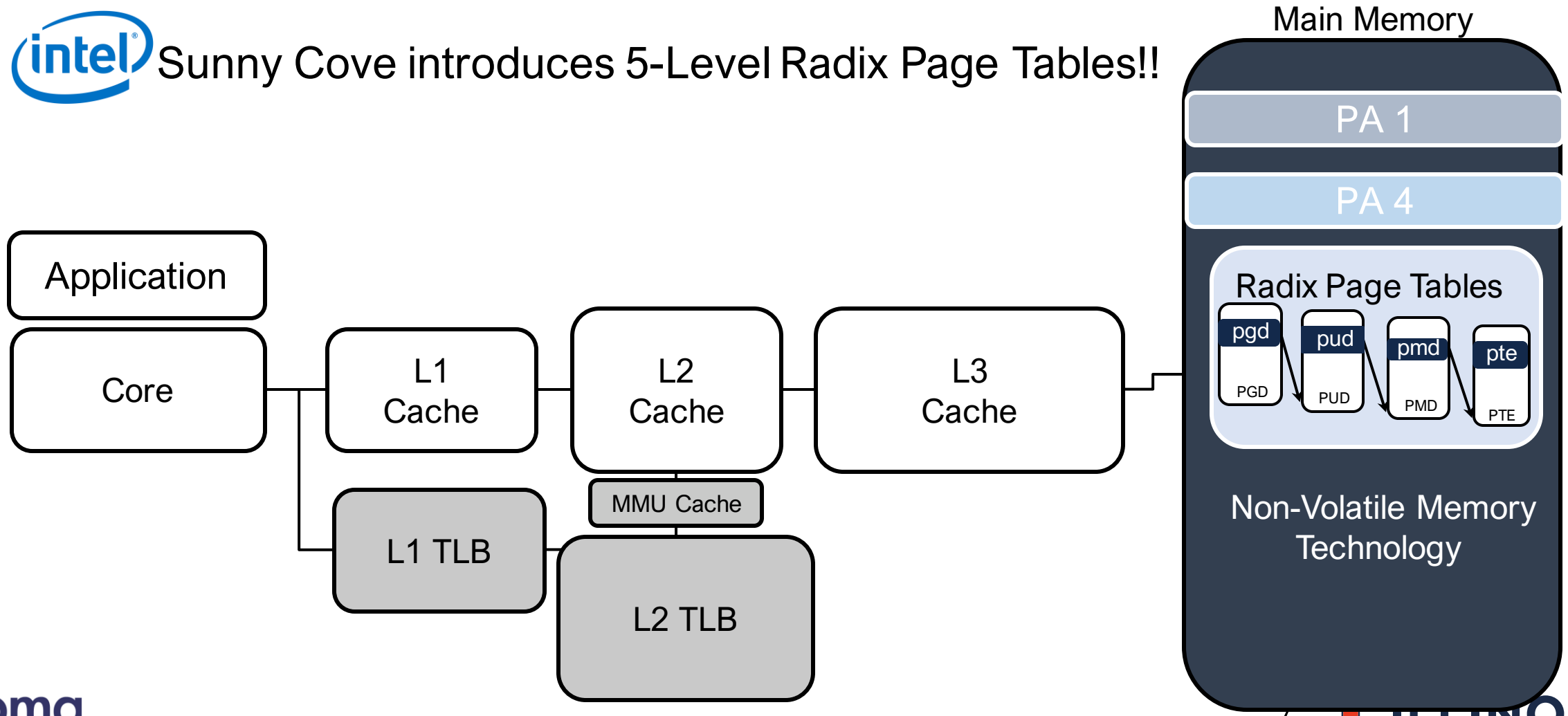
TLB Miss → "Page Walk" = Fetch entry from radix page table

Address Translation System



Even More Memory is Here!

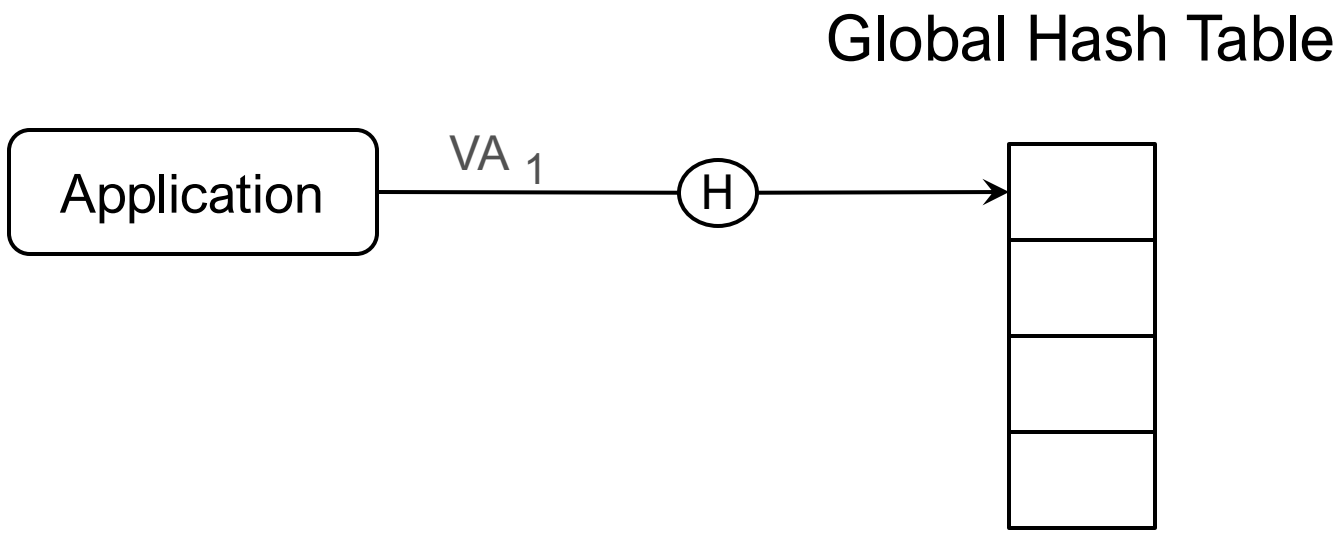
Sunny Cove introduces 5-Level Radix Page Tables!!



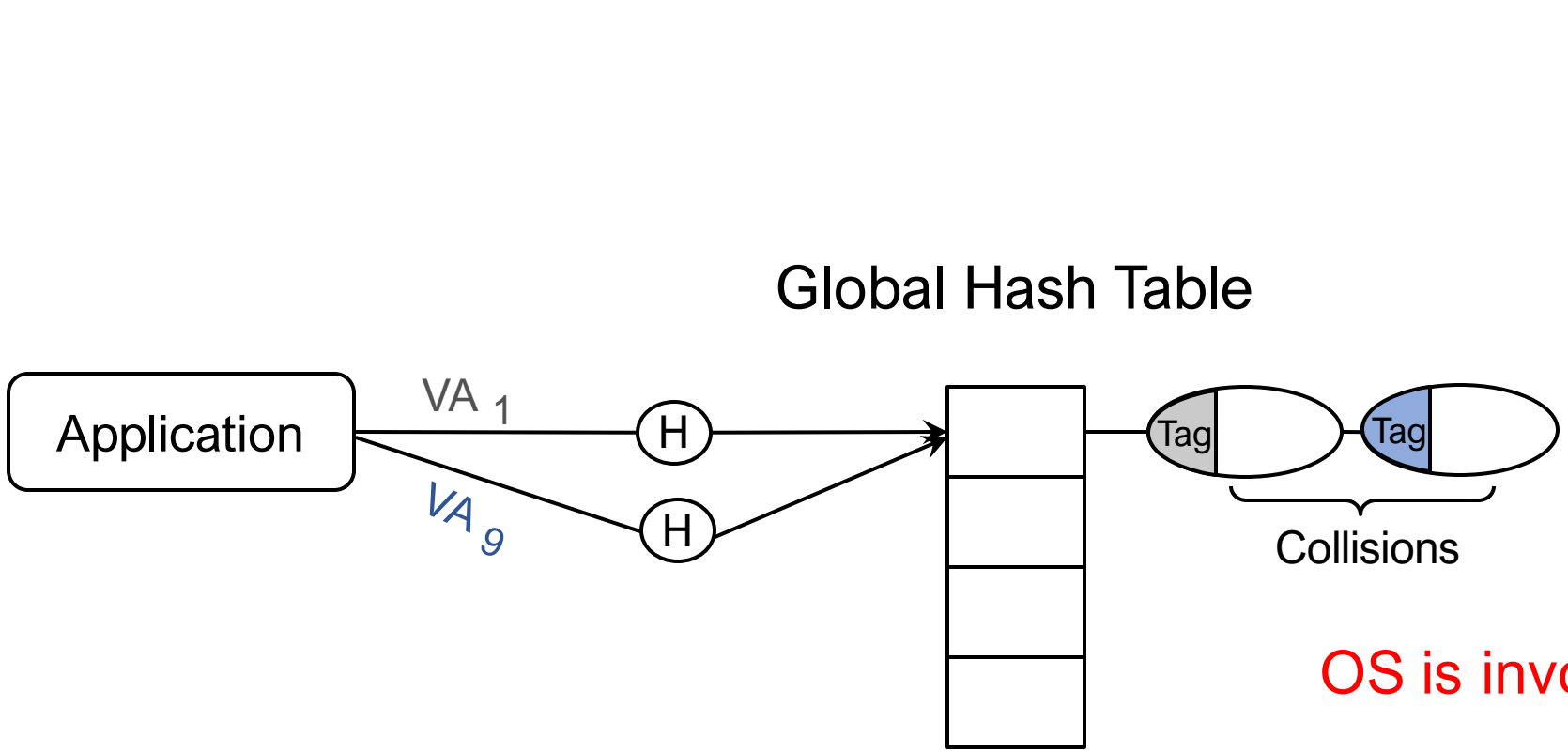
Time to Rethink Virtual Memory Translation

Current Radix Page Tables Are Not Scalable

Alternative: Global Hashed Page Table



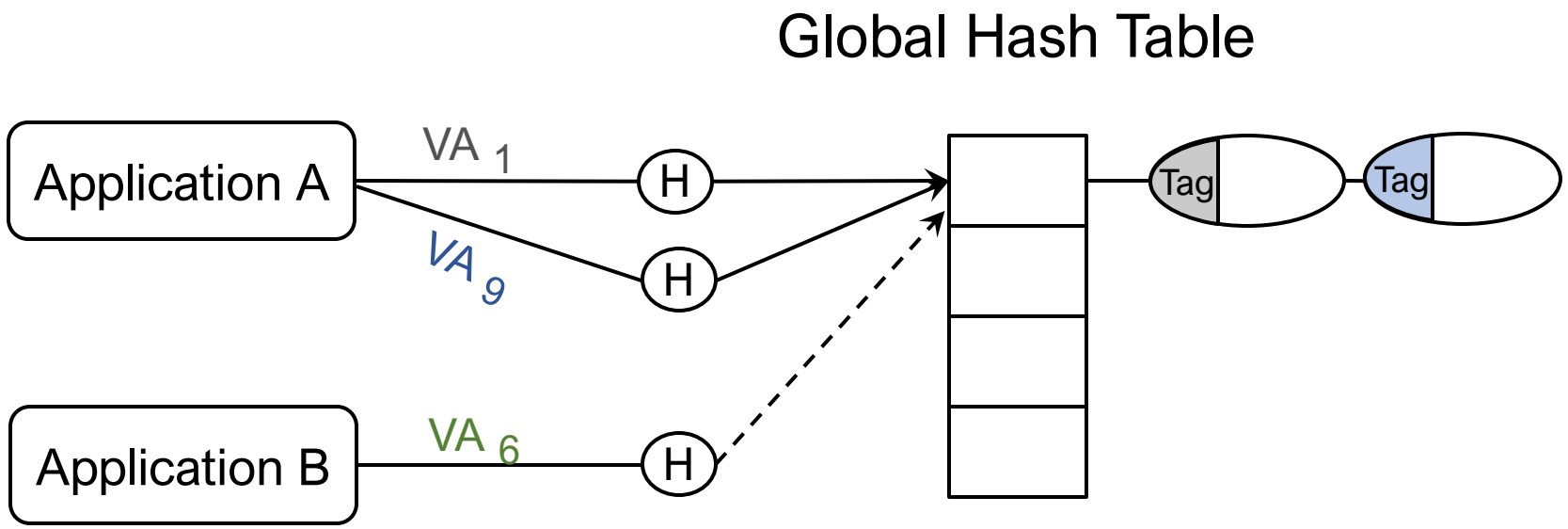
Alternative: Global Hashed Page Table



OS is invoked to resolve them!

Alternative: Global Hashed Page Table

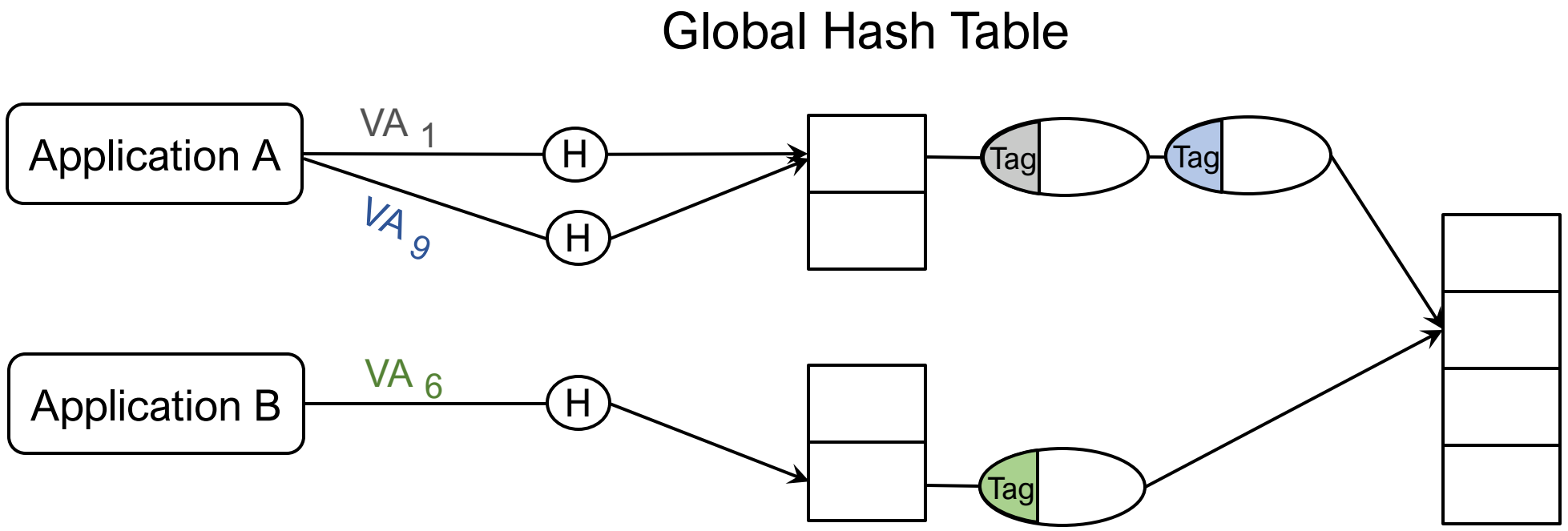
How to share pages?



Alternative: Global Hashed Page Table

How to share pages?

New level of indirection!!

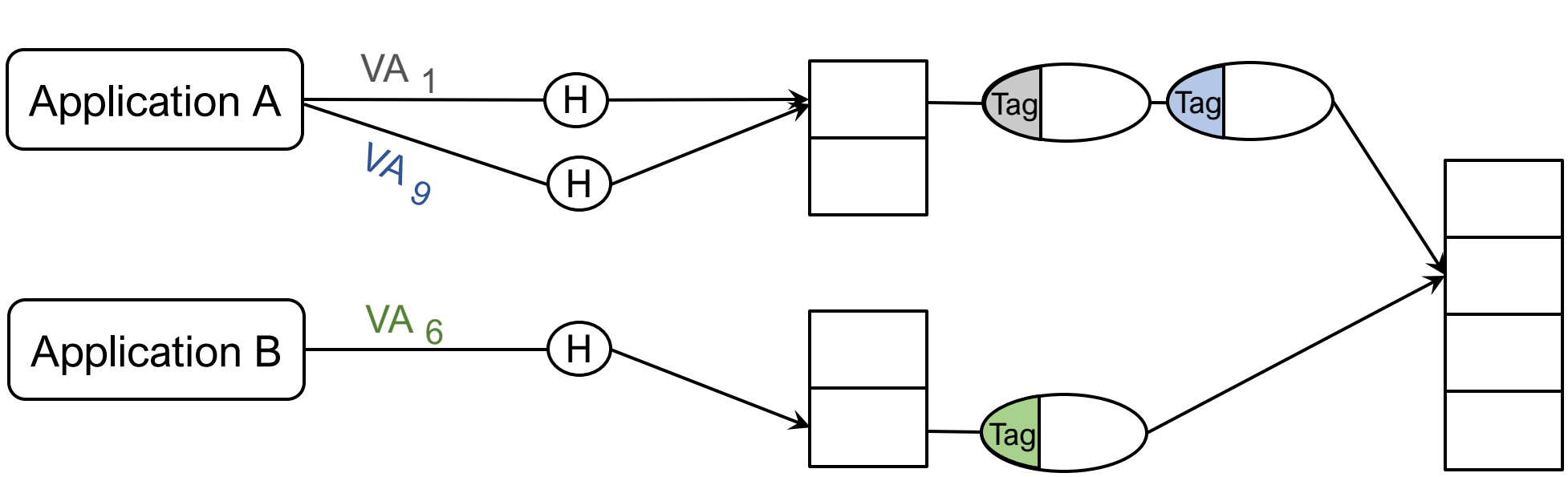


Alternative: Global Hashed Page Table

How to share pages?

Multiple page sizes?

New level of indirection!!

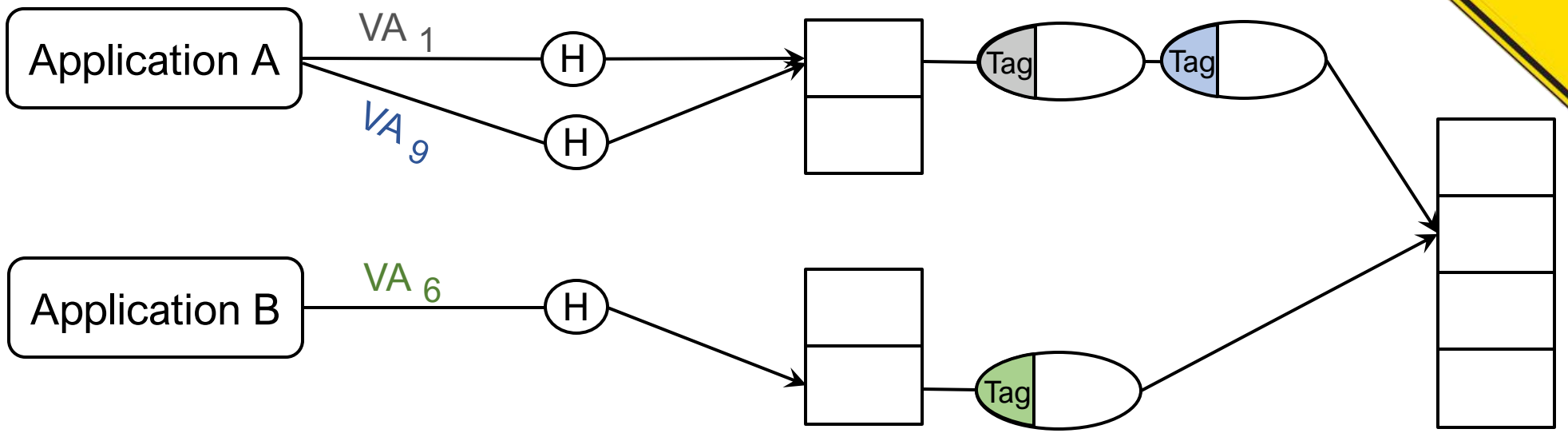


Alternative: Global Hashed Page Table

How to share pages?
Multiple page sizes?

New level of indirection!!

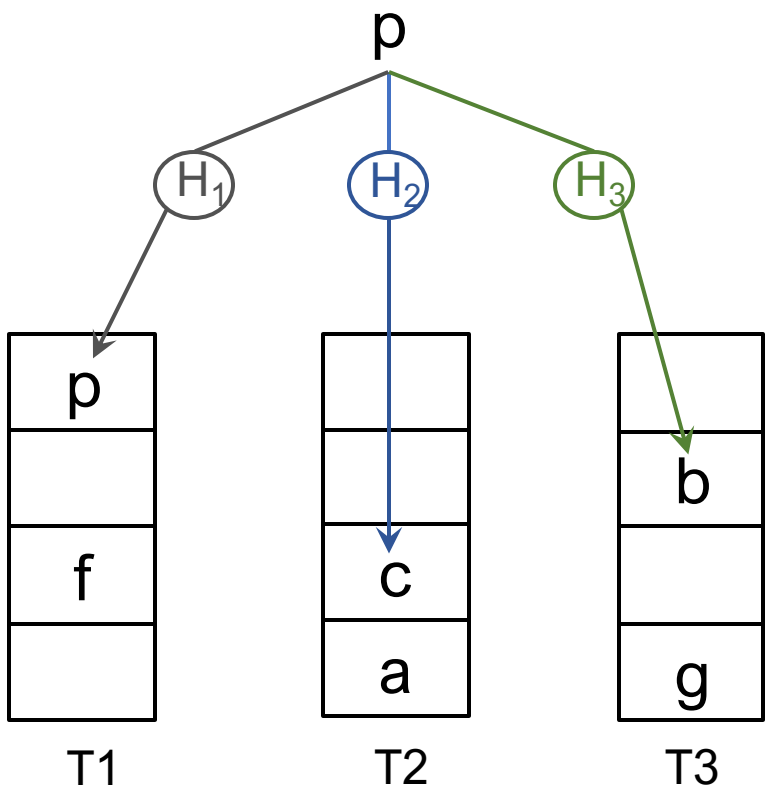
Global Hash Table



Elastic Cuckoo Page Tables

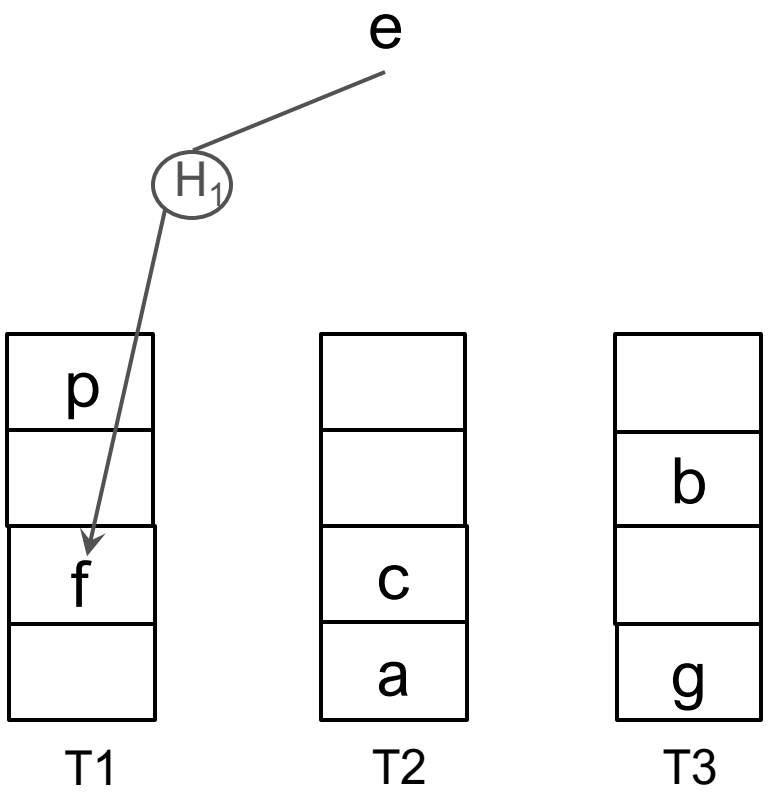
Rethinking virtual memory translation for parallelism

Cuckoo Hashing



d-ary Cuckoo Hash Table

Insertions with Cuckoo Hashing



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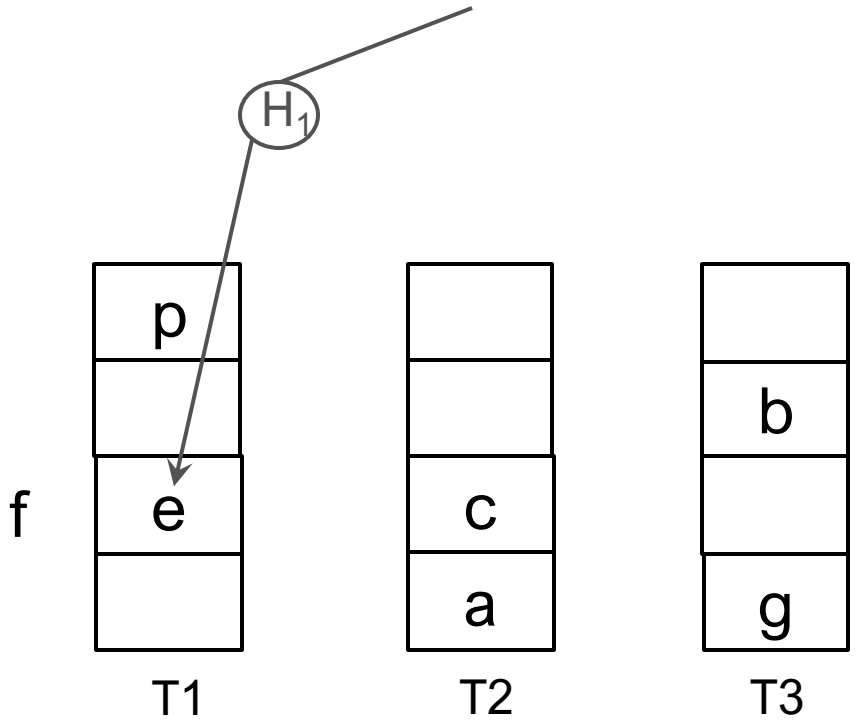

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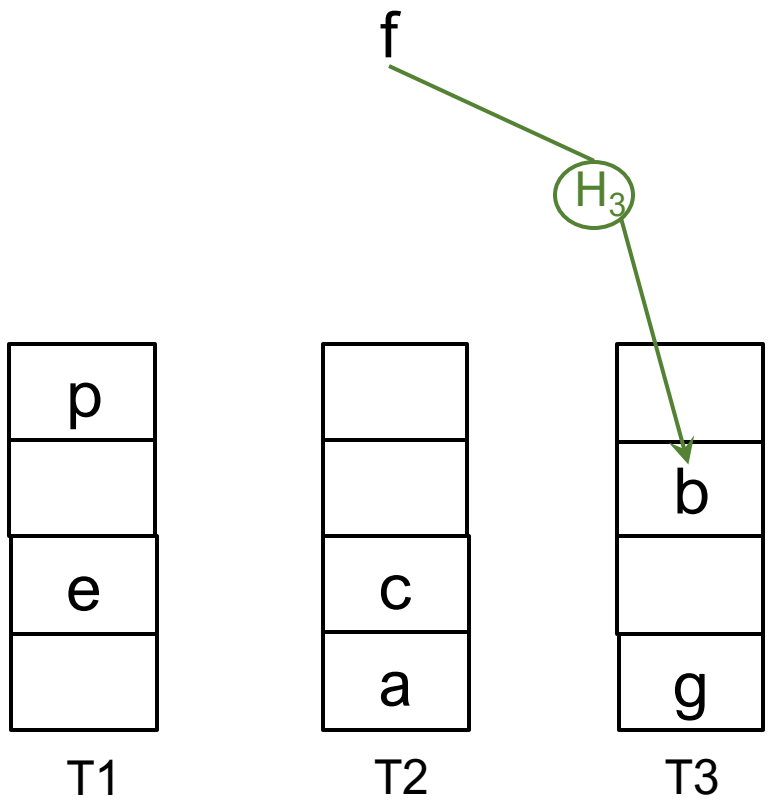

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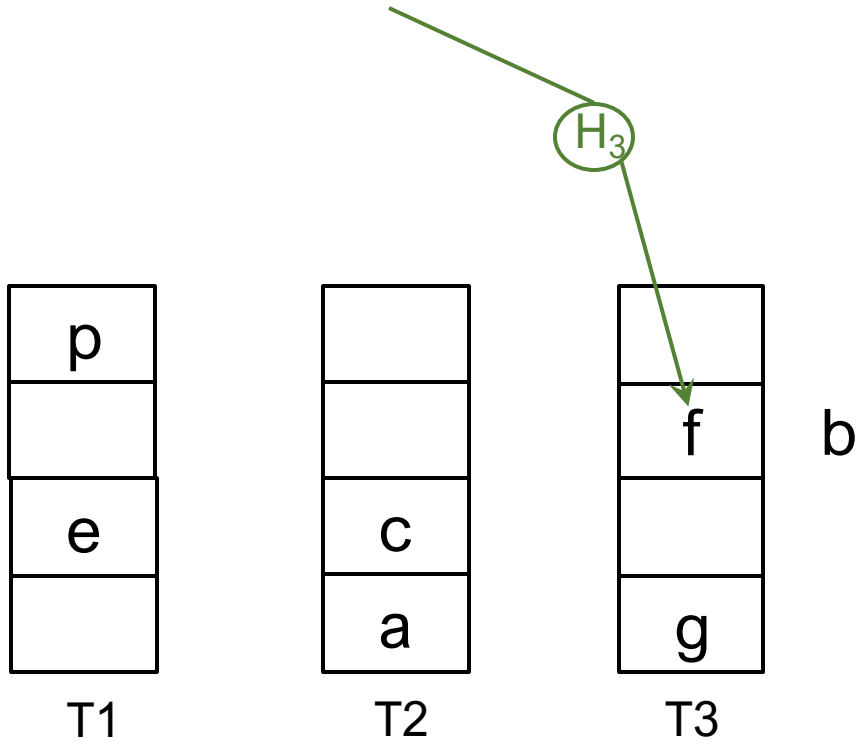

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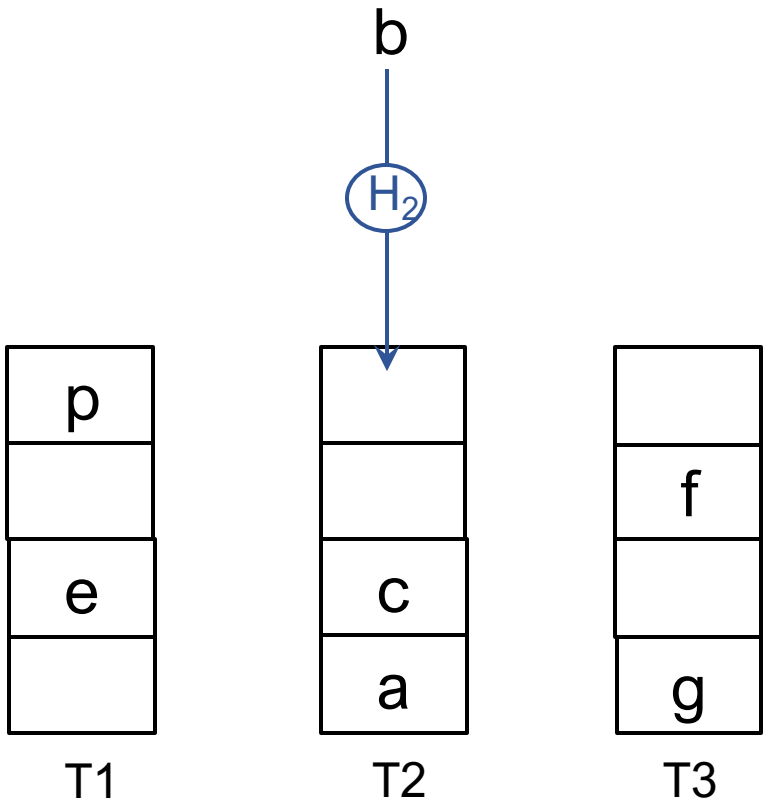

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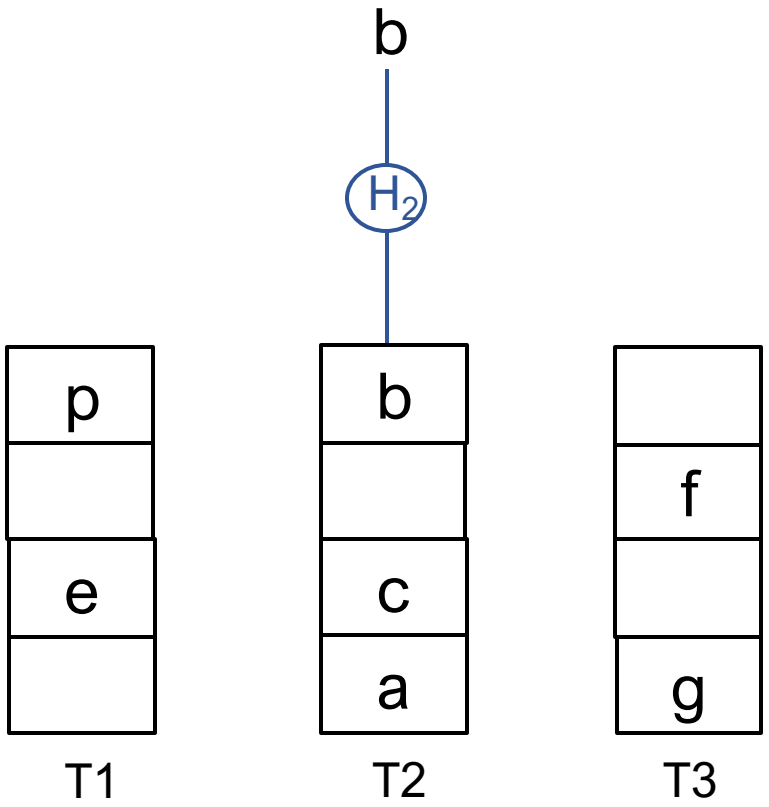
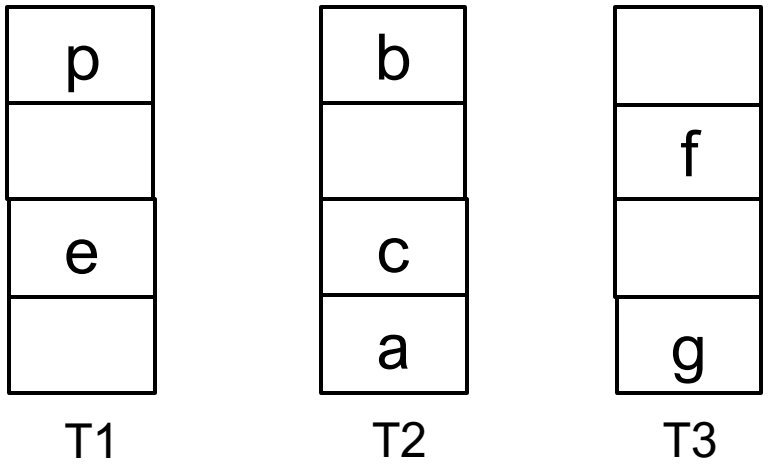


d-ary Cuckoo Hash Table

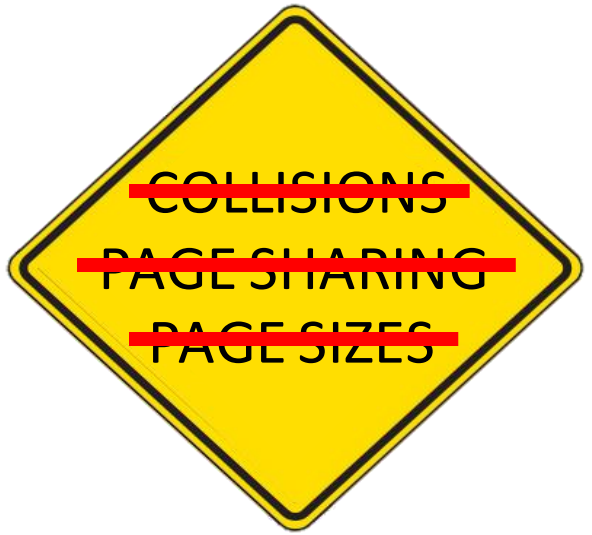
Insertions with Cuckoo Hashing

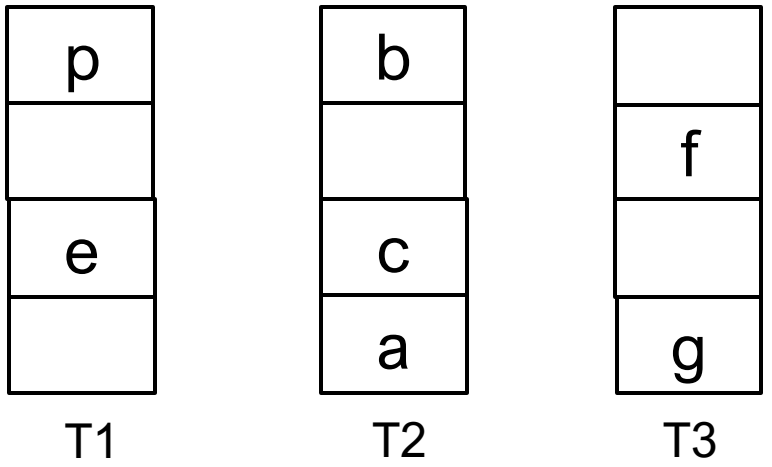


d-ary Cuckoo Hash Table

Private Hashed Page Tables

PRIVATE
PAGE TABLES





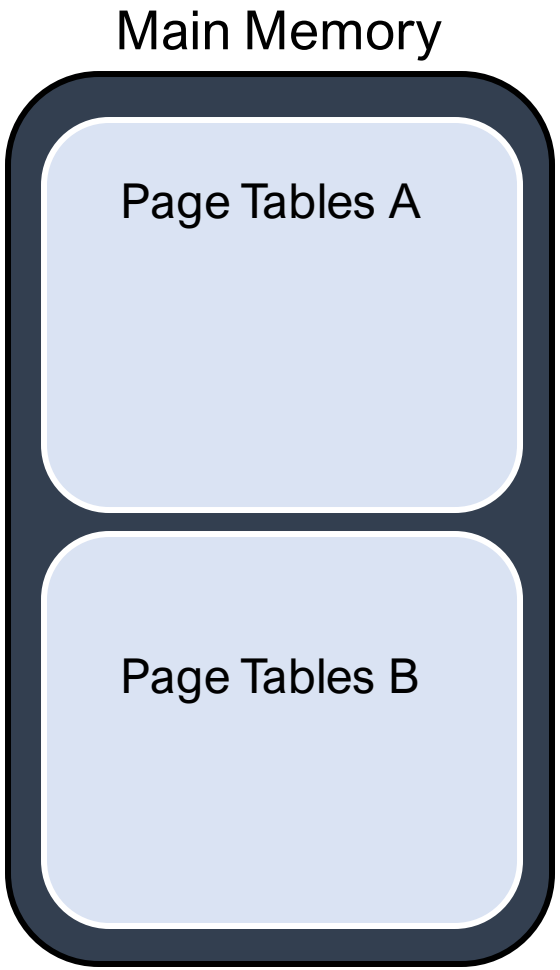
d-ary Cuckoo Hash Table

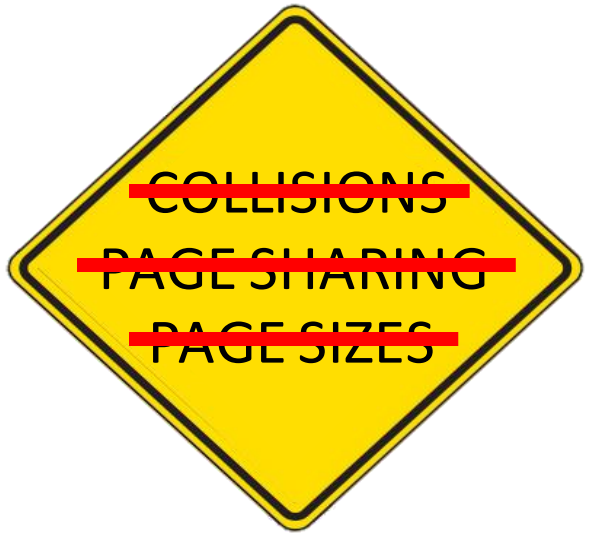
Cannot Be Too Big → Waste Memory

PRIVATE PAGE TABLES

App A

App B





Private page tables cannot be too big

Need to Dynamically Resize

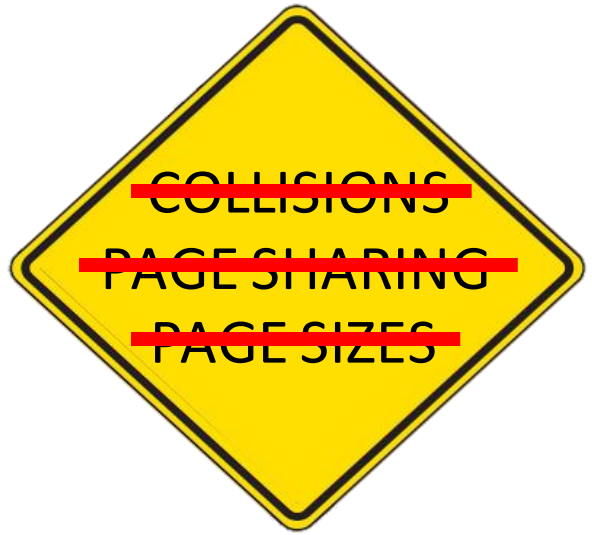
PRIVATE PAGE TABLES

App A

Main Memory

Page Tables A

VA 1	PA 4
VA 8	PA 1



Private page tables cannot be too big

↓

Need to dynamically resize

Cannot Rehash All Entries at Once

PRIVATE PAGE TABLES

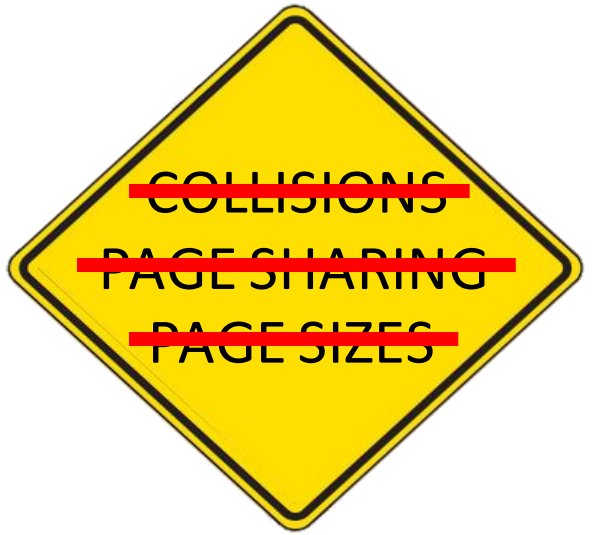
App A

Main Memory

Page Tables A

VA 1	PA 4
VA 8	PA 1

New Page Tables A



Private page tables cannot be too big

↓

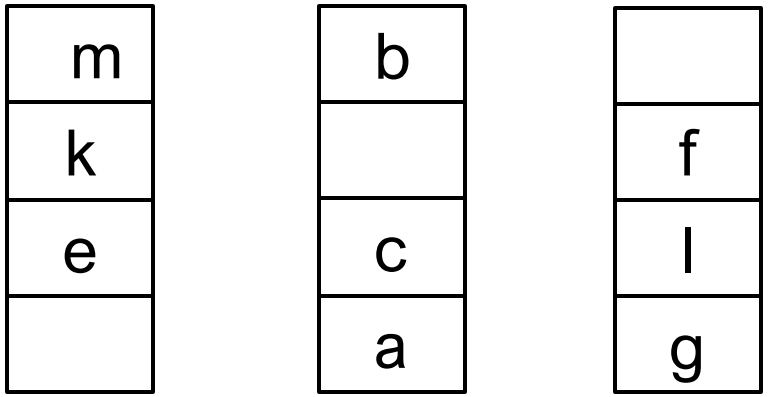
Need to dynamically resize

↓

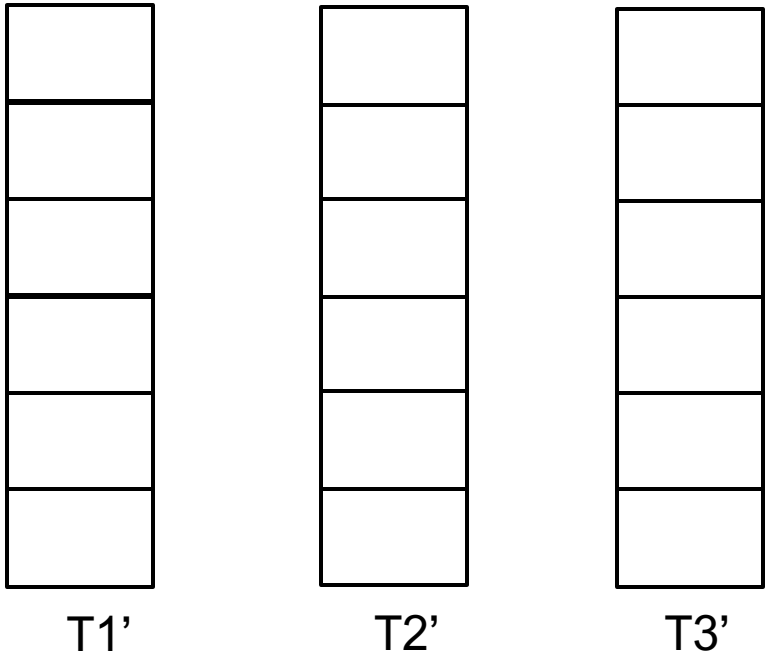
GRADUAL REHASHING
while the program is running

Gradual Rehashing of Cuckoo Hash Tables

At every insert → Rehash one element



Old *d*-ary Cuckoo Hash Table



New *d*-ary Cuckoo Hash Table

Gradual Rehashing of Cuckoo Hash Tables

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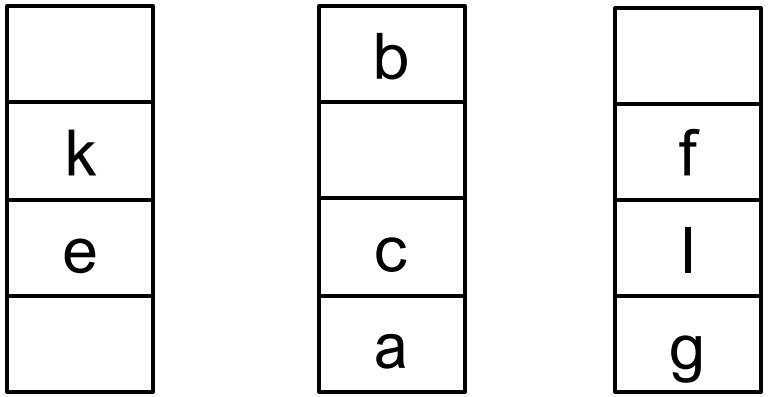
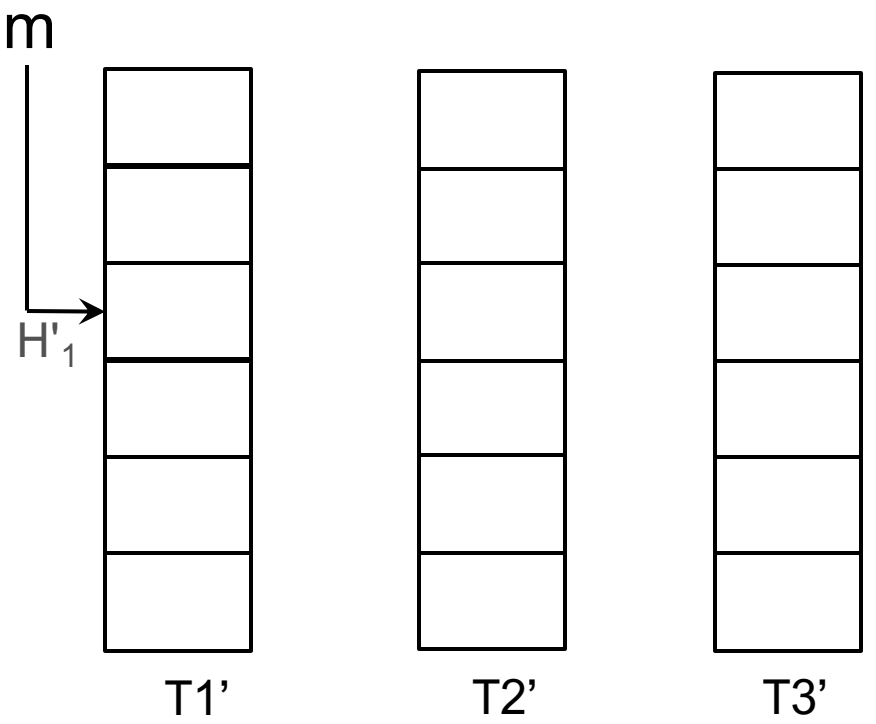
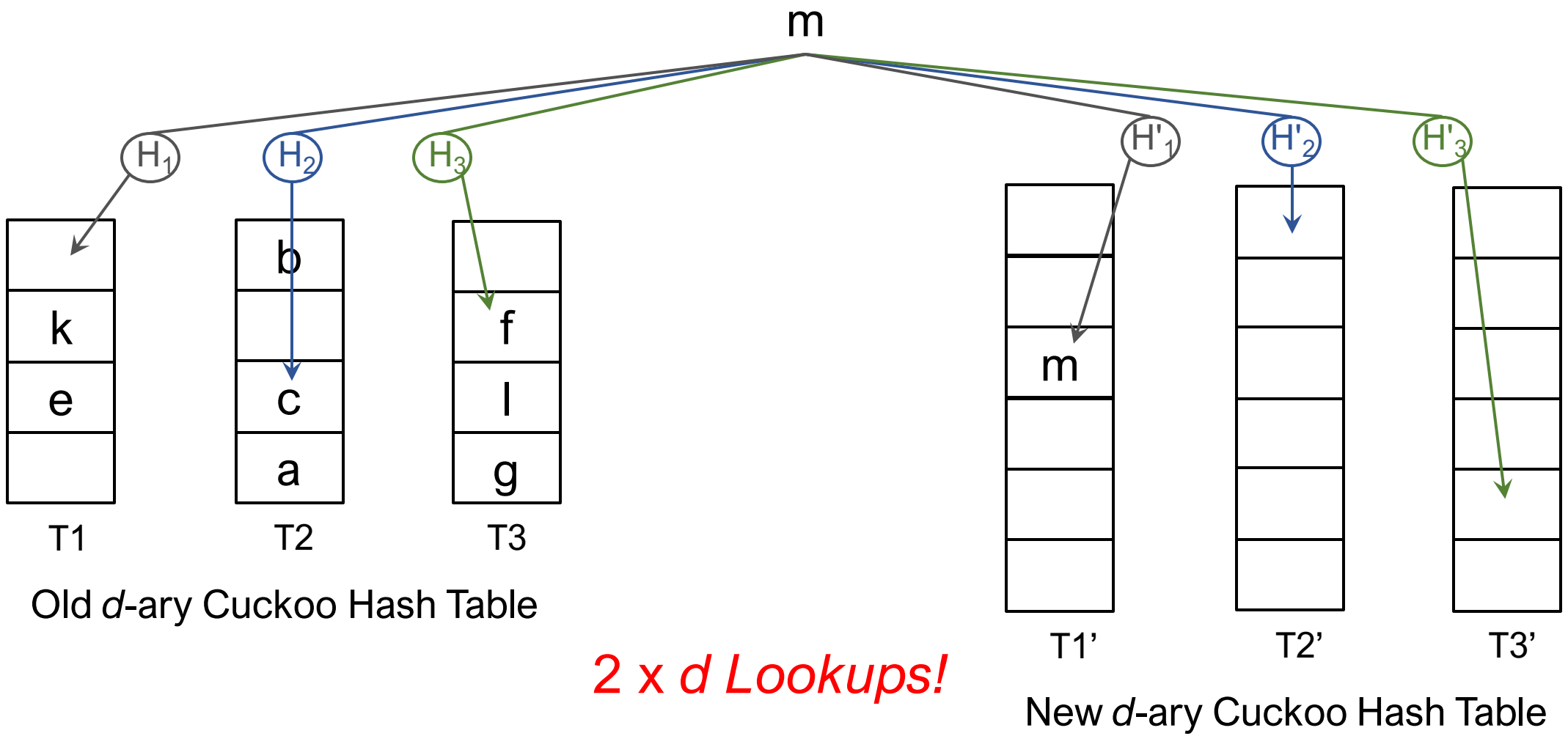


Old *d*-ary Cuckoo Hash Table

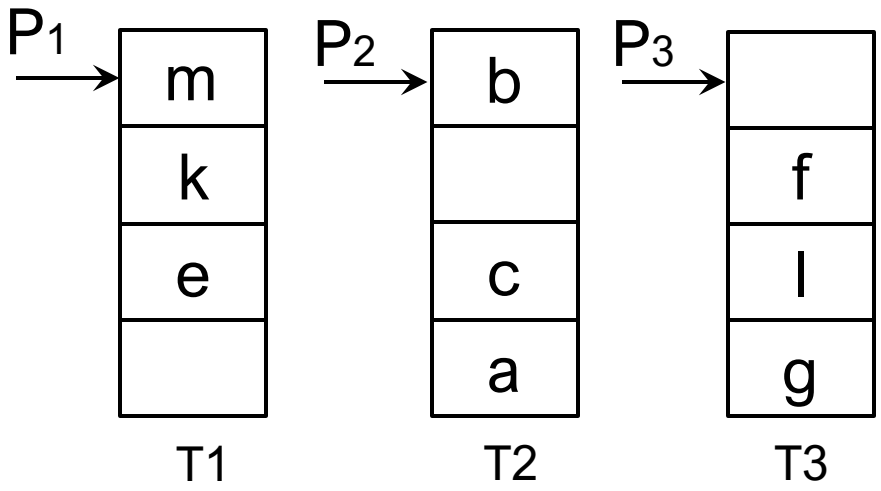


New *d*-ary Cuckoo Hash Table

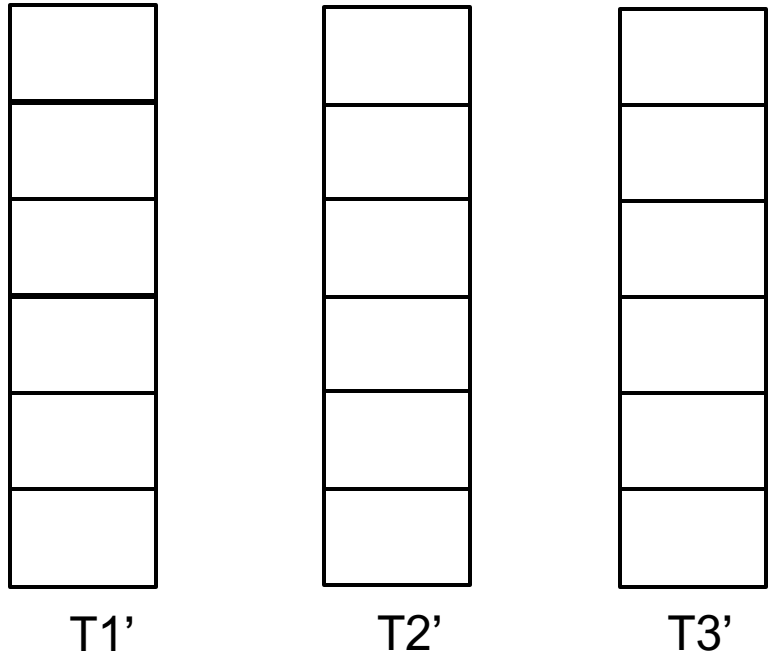
Lookup During Gradual Rehashing



Solution: Rehashing Pointers

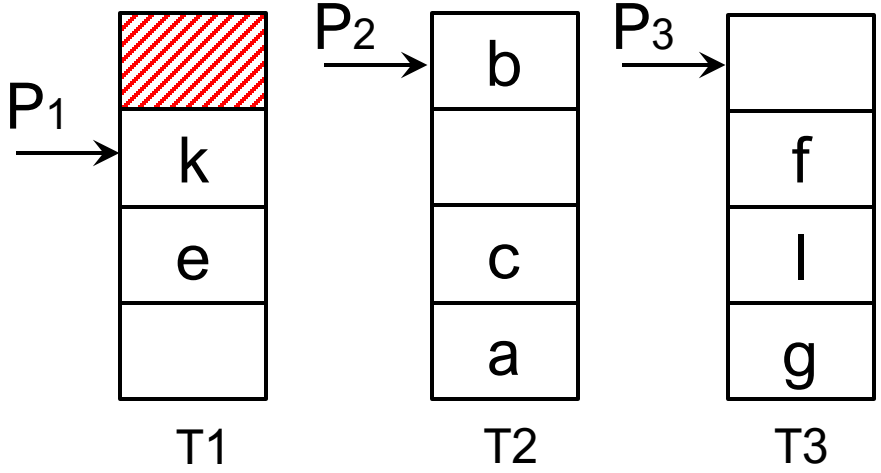


Old *d*-ary Cuckoo Hash Table



New *d*-ary Cuckoo Hash Table

Solution: Rehashing Pointers



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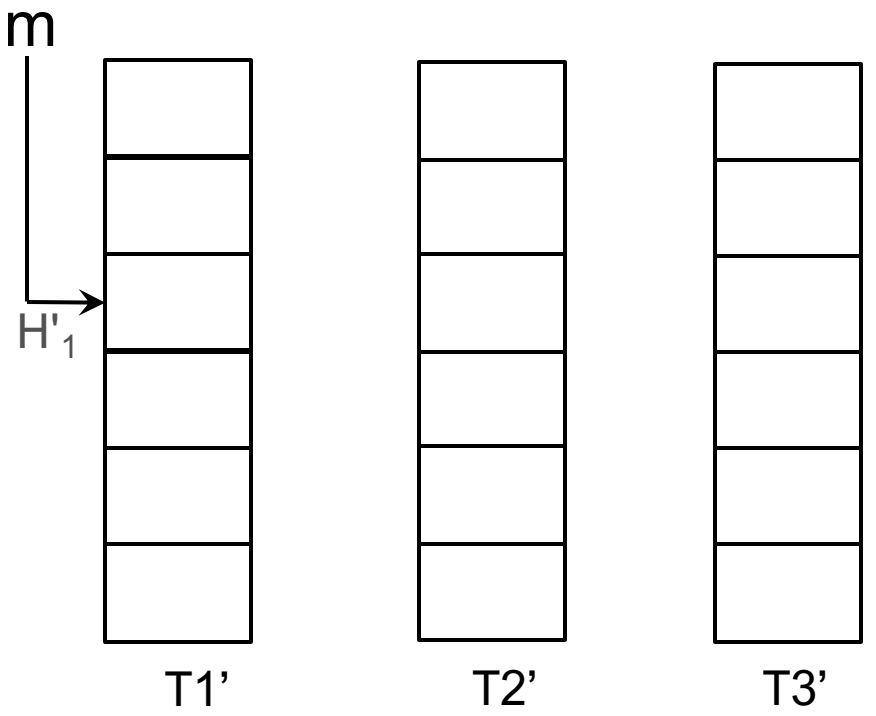
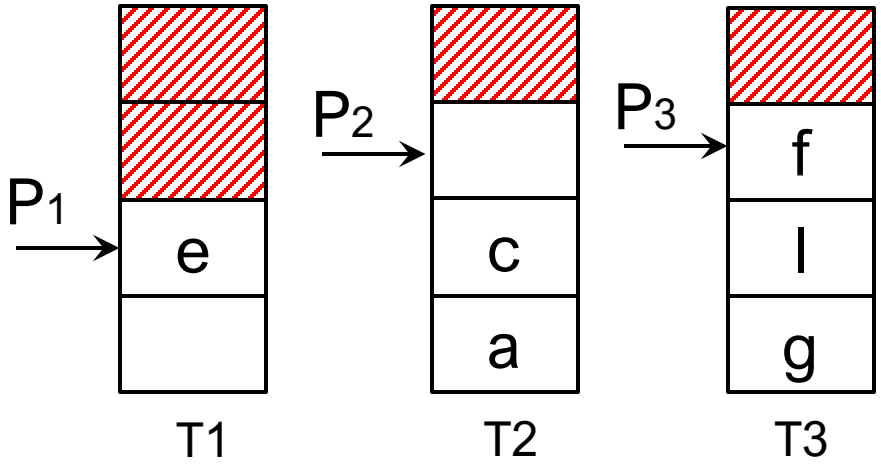


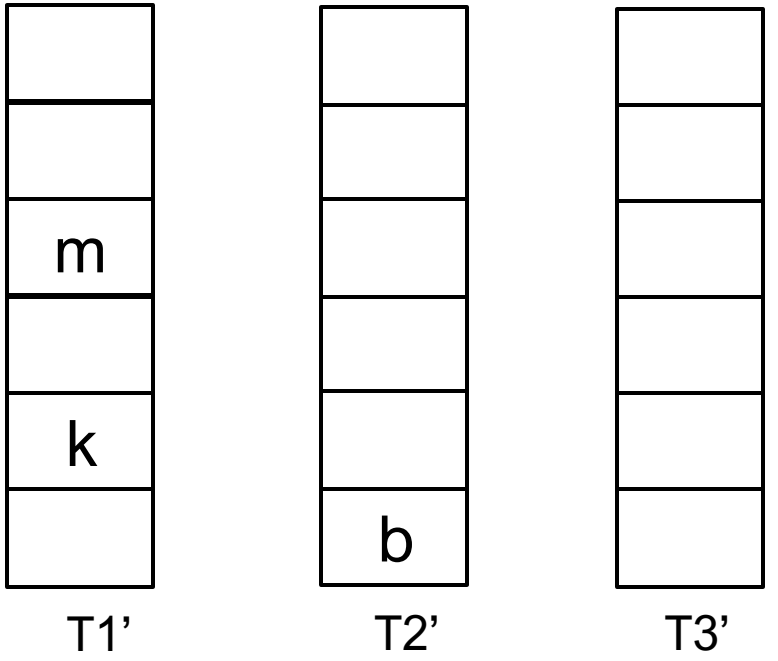
New *d*-ary Cuckoo Hash Table

Migrated Region

Solution: Rehashing Pointers



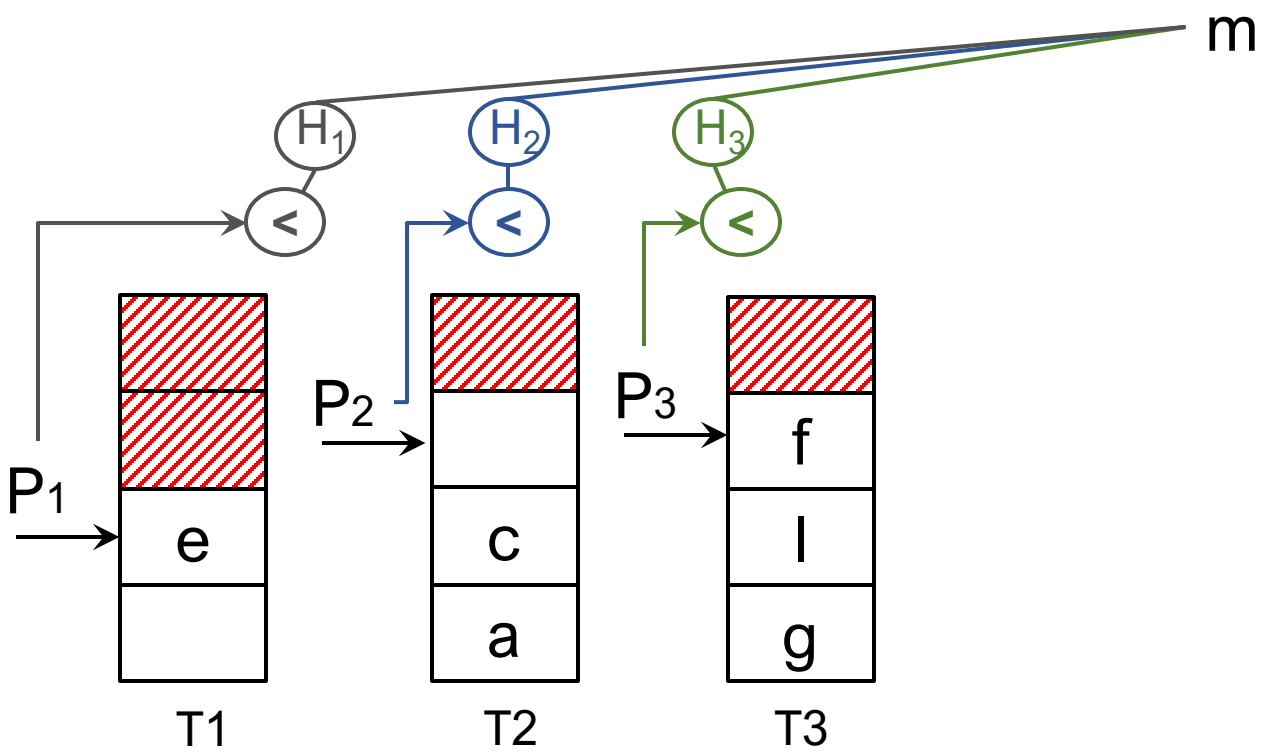
Old *d*-ary Cuckoo Hash Table



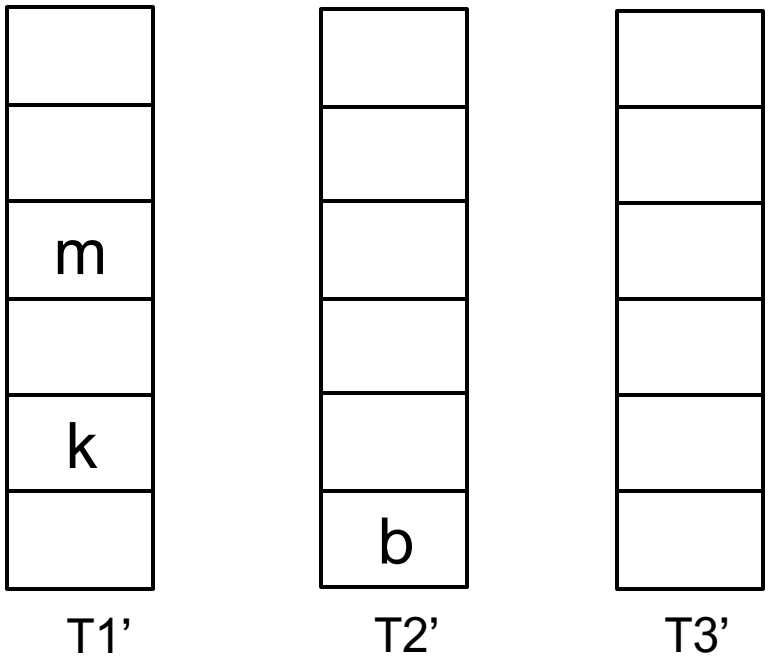
New *d*-ary Cuckoo Hash Table

Migrated Region

Lookup with Rehashing Pointers



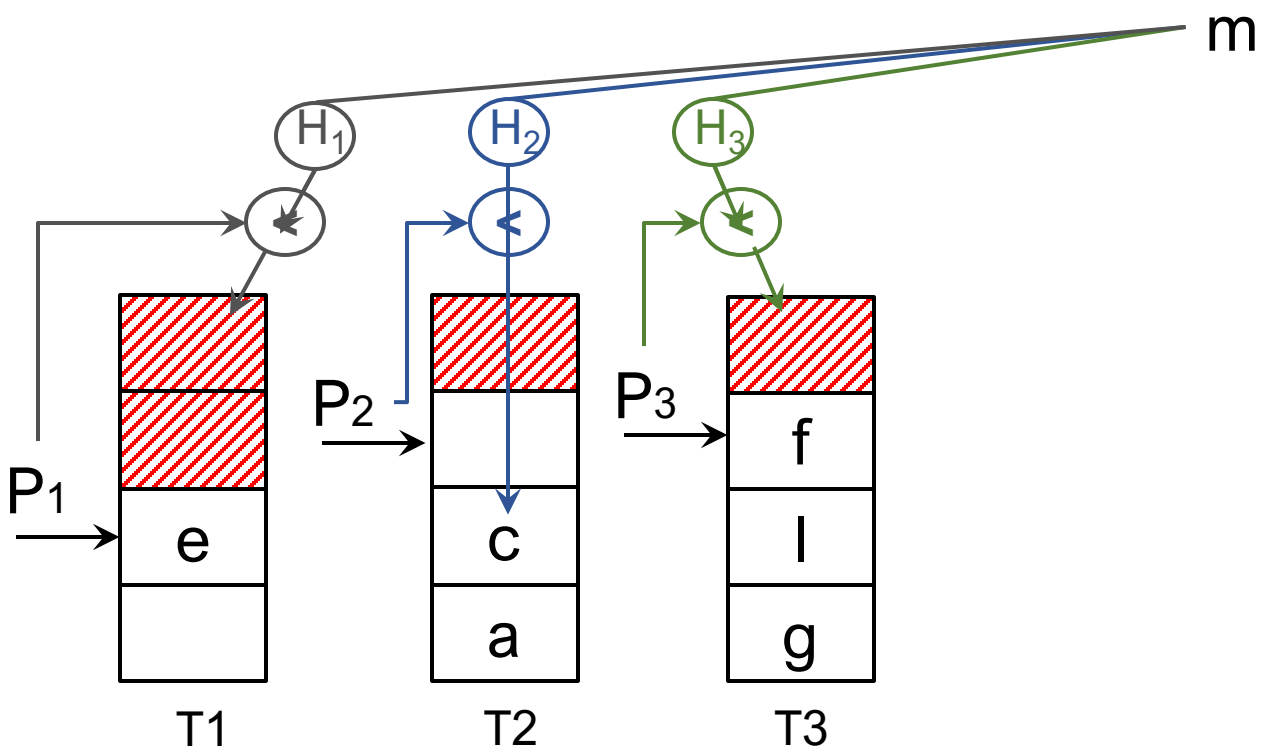
Old *d*-ary Cuckoo Hash Table



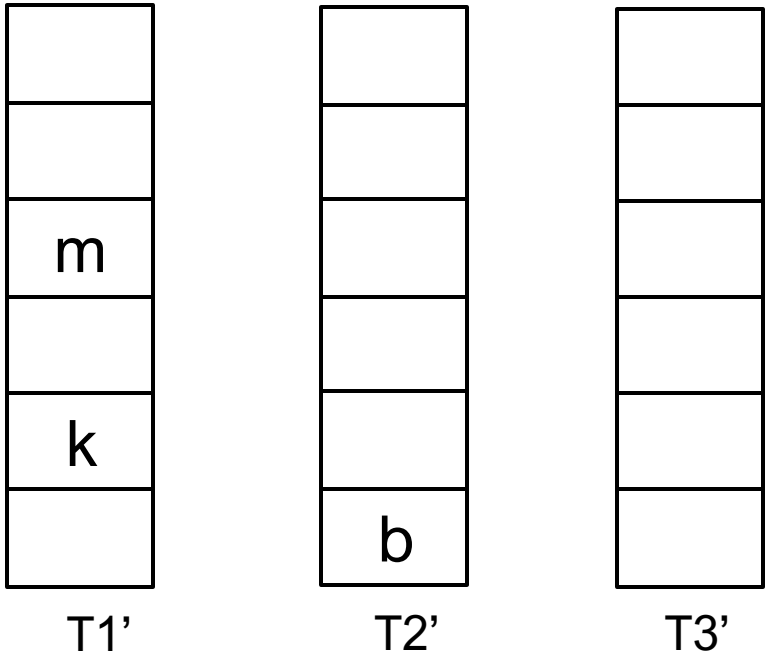
New *d*-ary Cuckoo Hash Table

Migrated Region

Lookup with Rehashing Pointers



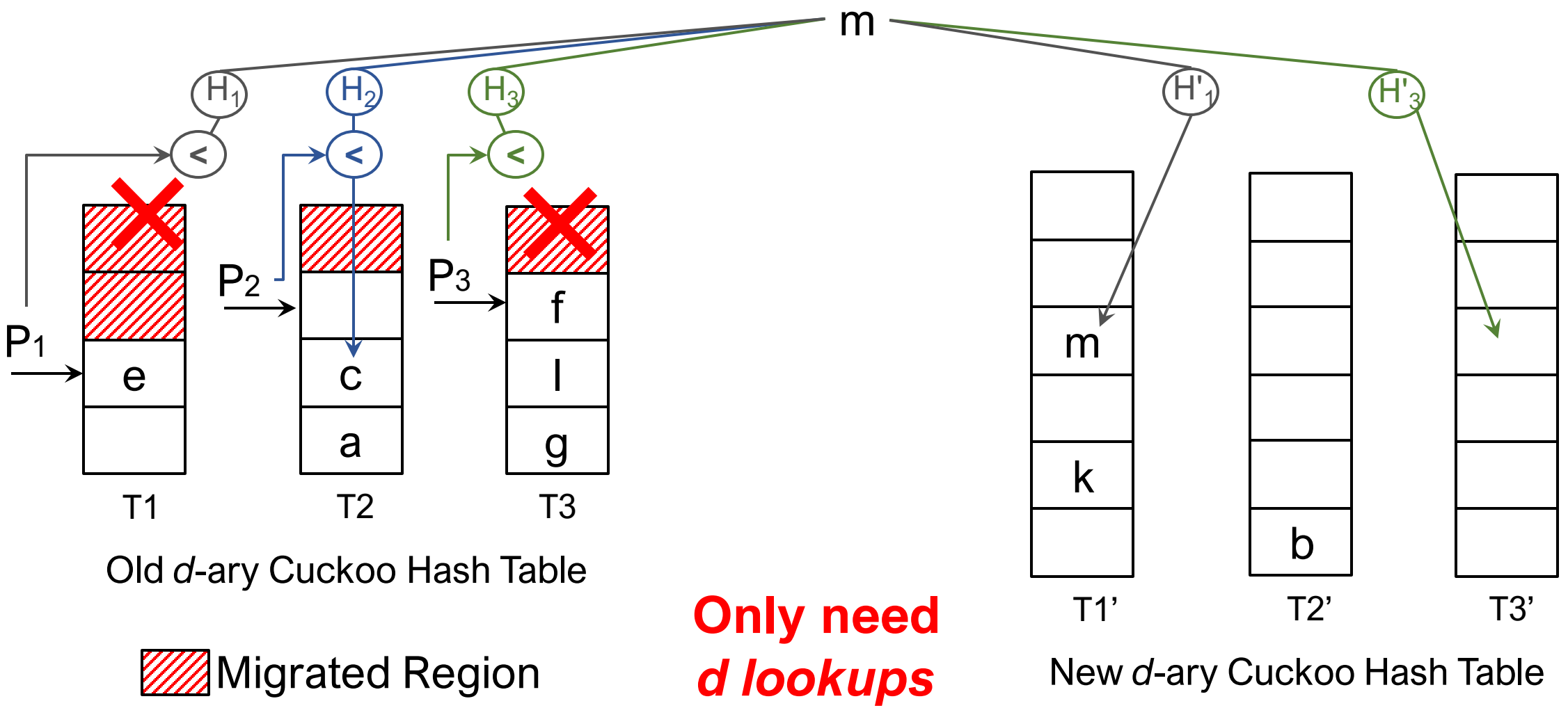
Old *d*-ary Cuckoo Hash Table



New *d*-ary Cuckoo Hash Table

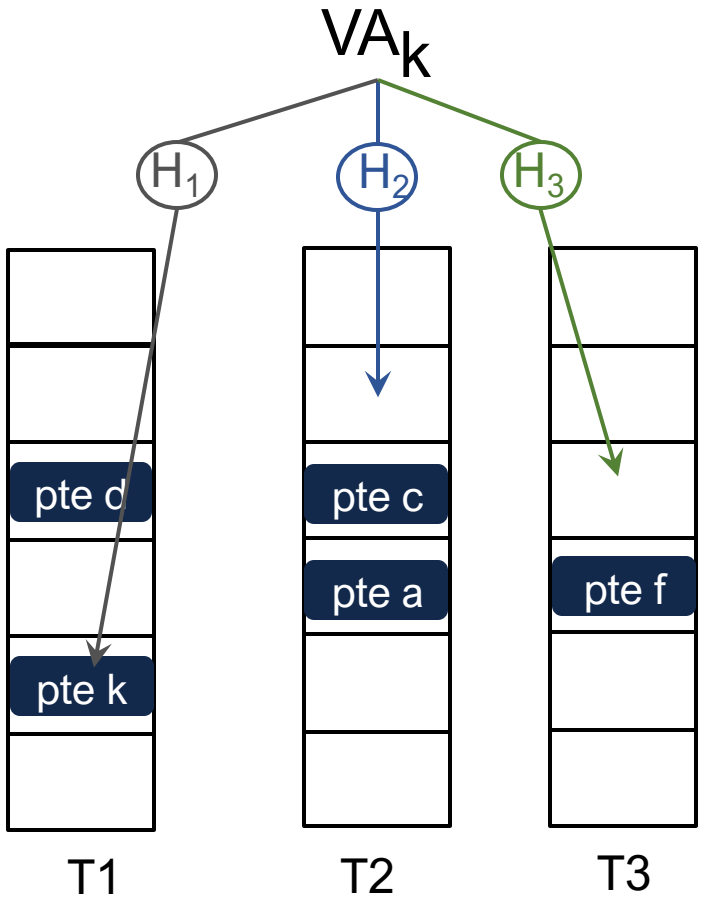
Migrated Region

Lookup with Rehashing Pointers



Only need *d lookups* *during resizing*

Exploiting Parallelism in Virtual Translation



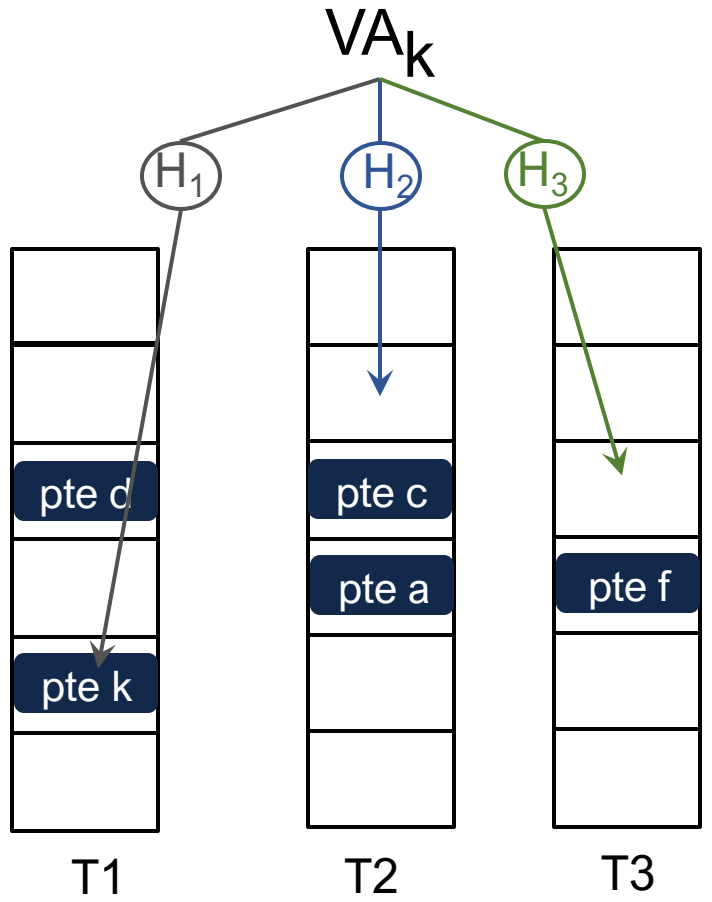
d-ary Elastic Cuckoo Page Table

Exploiting Parallelism in Virtual Translation

No sequential page walk (*unlike radix*)

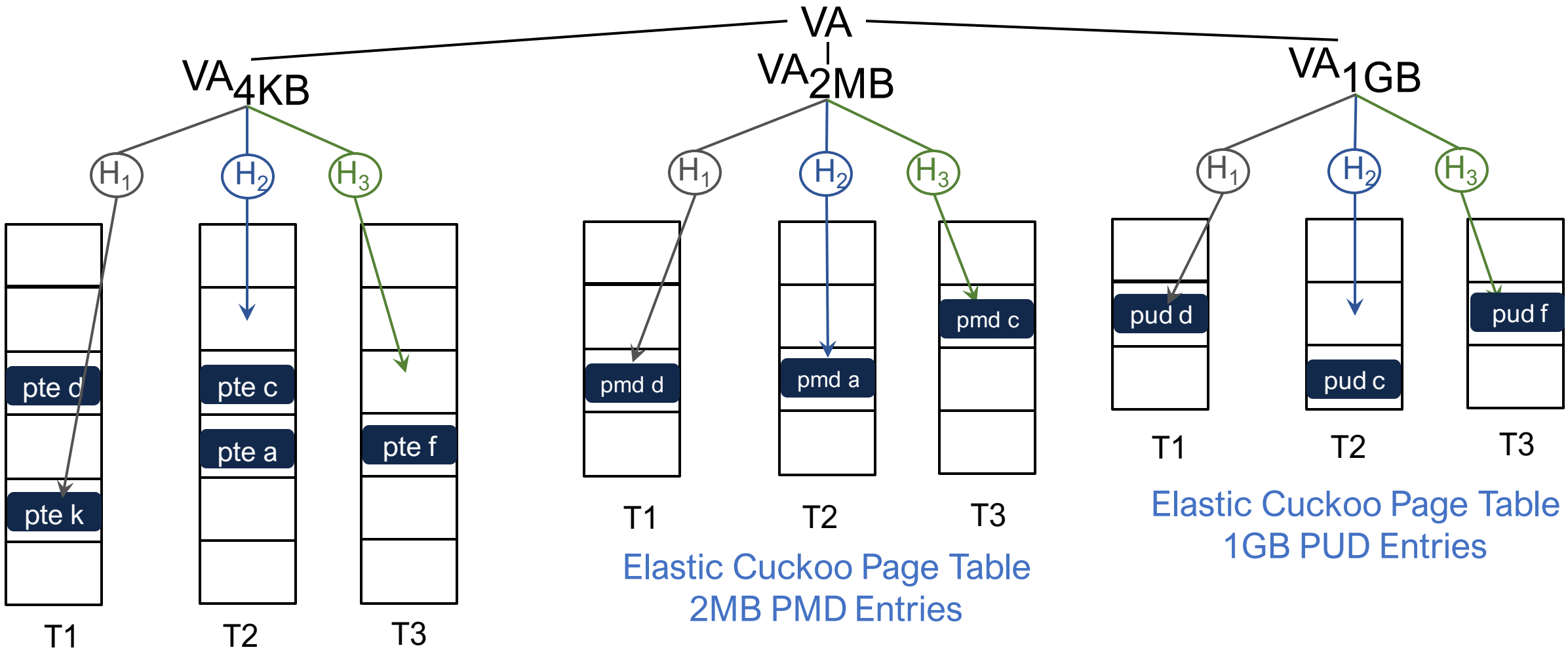
At most *d* accesses *always*

Leverages multiple issue out-of-order processors



d-ary Elastic Cuckoo Page Table

Lookup Multiple Page Sizes in Parallel



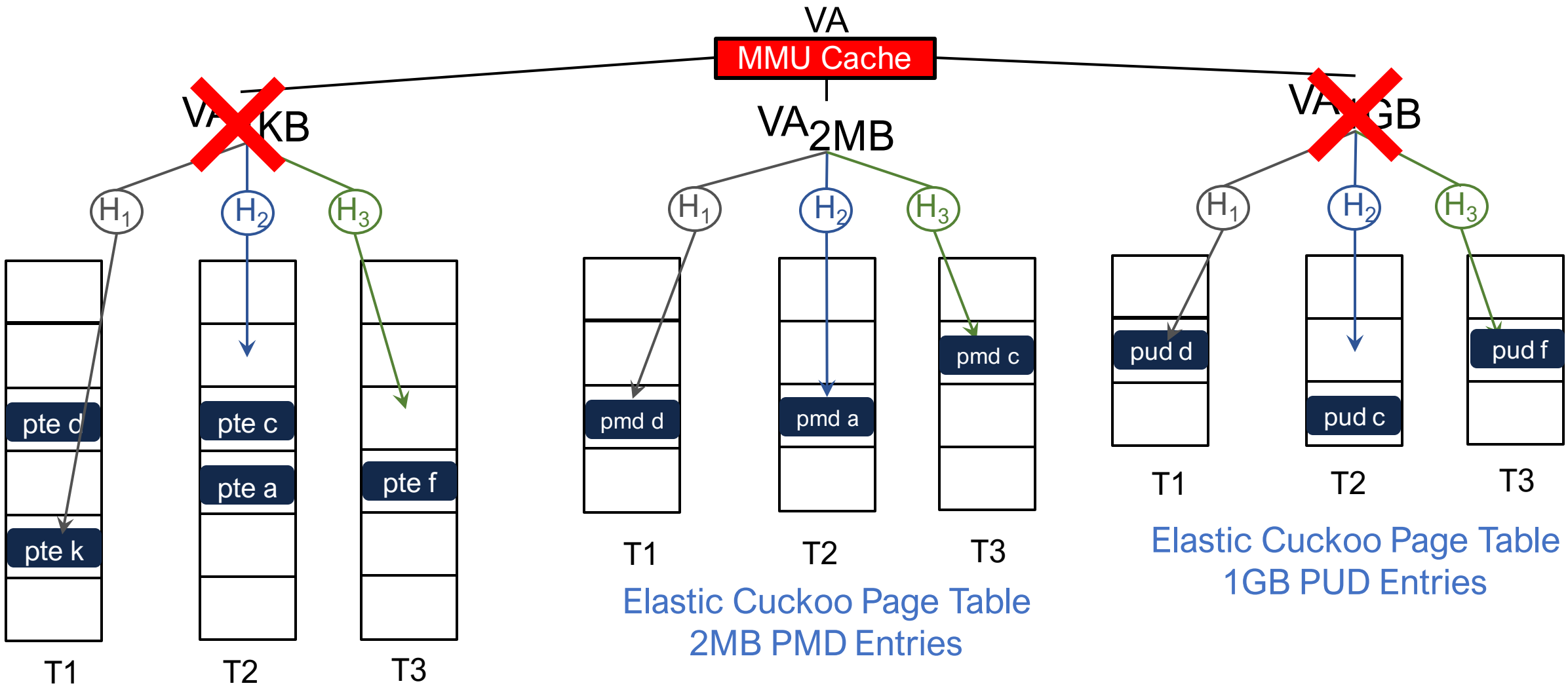
d-ary Elastic Cuckoo Page Table
4KB PTE Entries

Elastic Cuckoo Page Table
2MB PMD Entries

Elastic Cuckoo Page Table
1GB PUD Entries

ILLINOIS

New MMU Cache to Prune Parallelism



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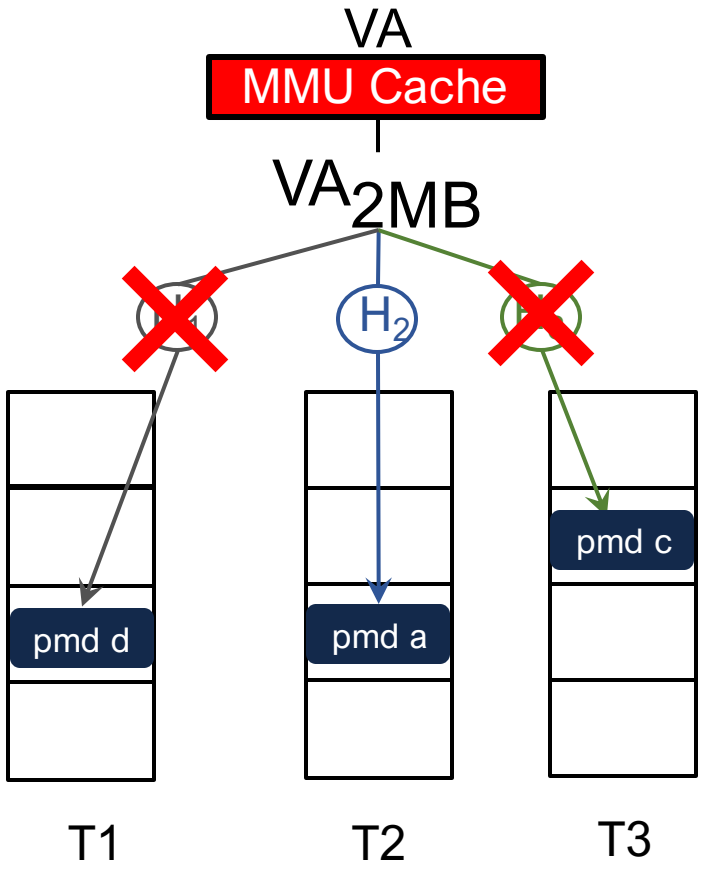
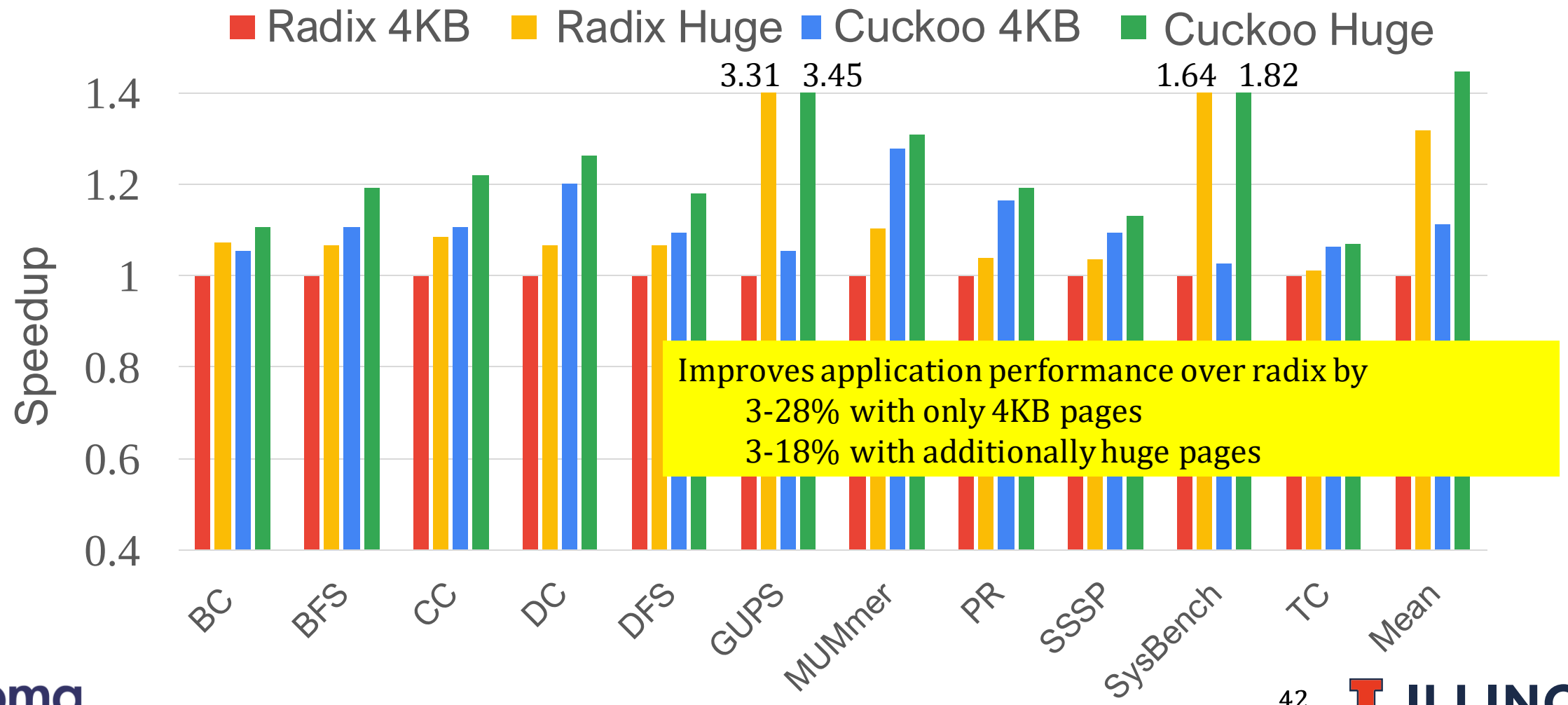


Elastic Cuckoo Page Table
2MB PMD Entries

Application Speedup



Takeaway: Elastic Cuckoo Page Tables

Scalable alternative to existing radix page tables

- Exploits parallelism in virtual translation for the first time
- Reduces the cost of hash table resizing
- Improves application performance over radix by
  - 3-28% with only 4KB pages
  - 3-18% with additionally huge pages
- Expect even higher performance impact on virtualized environments
- Current work: graceful migration from current Radix designs to Elastic Cuckoo

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University of Illinois at Urbana-Champaign
http://iacoma.cs.uiuc.edu

ARM Research Summit
September 2020