SmartCuckoo: A Fast and Cost-Efficient Hashing Index Scheme for Cloud Storage Systems

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Indexing services in cloud storage

- Large amounts of data
  - From small hand-held devices to large-scale data centers
  - 44ZB in total, 5.2TB for each user in 2020 (IDC' 2014)

- Fast query services are important to both users and systems
  - Returning accurate results in a real-time manner
  - Improving system performance and storage efficiency

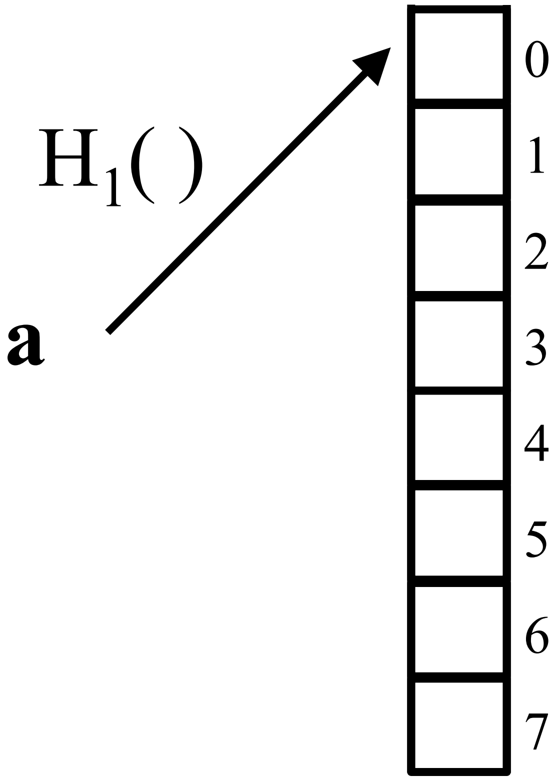
The importance of hash tables

- Hash tables are widely used in data stores and caches
  - Key-value stores, e.g., Memcached, Redis
  - Relational databases, e.g., MonetDB, HyPer
  - In-cache index (ICS 2014, MICRO 2015)
- Strengths:
  - Constant-scale addressing complexity ~O(1)
  - Fast query response
- Weakness:
  - Risk of high-latency for handling hashing collisions
- Cuckoo hashing

Cuckoo hashing

- Kick-out operations: like cuckoo birds
- Open addressing
- Supporting fast lookups: O(1) time complexity
- However, insertion latency can be very high and unpredictable, especially
  - **when an endless loop occurs!**

How is an endless loop formed?



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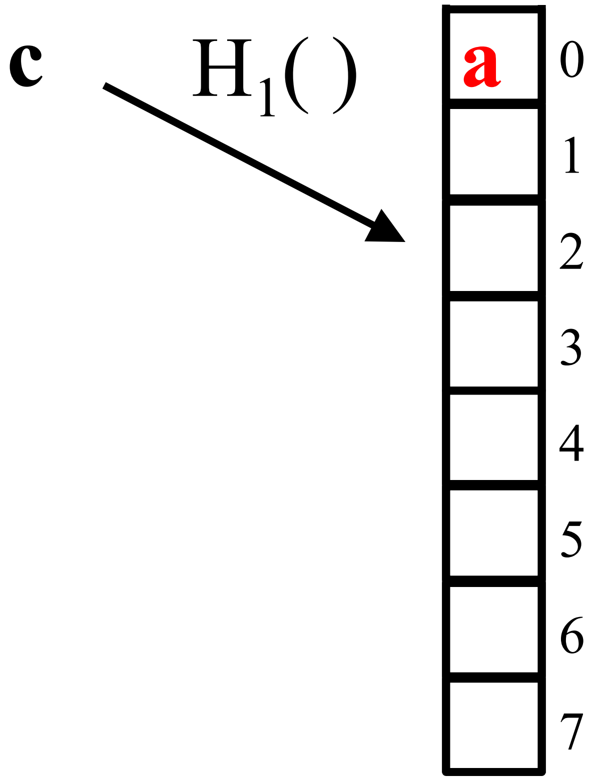

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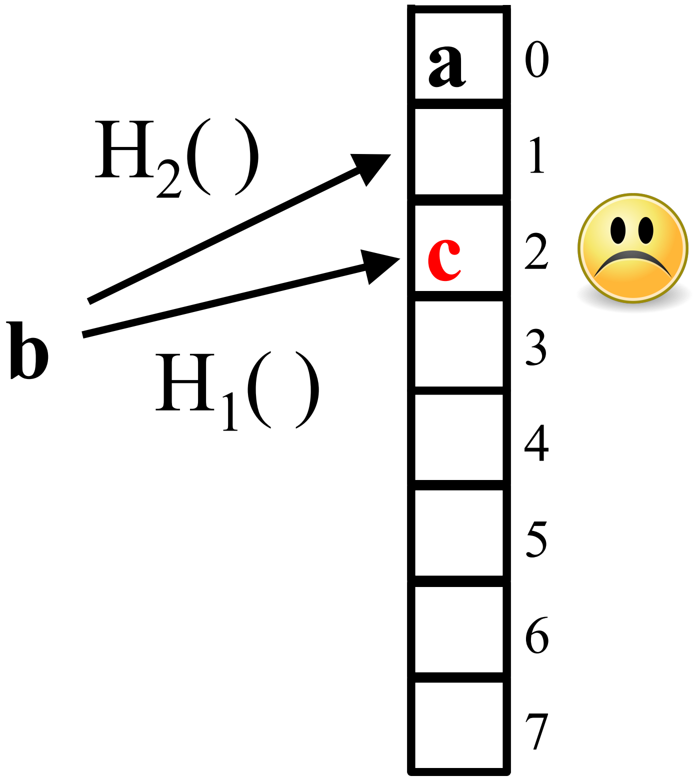

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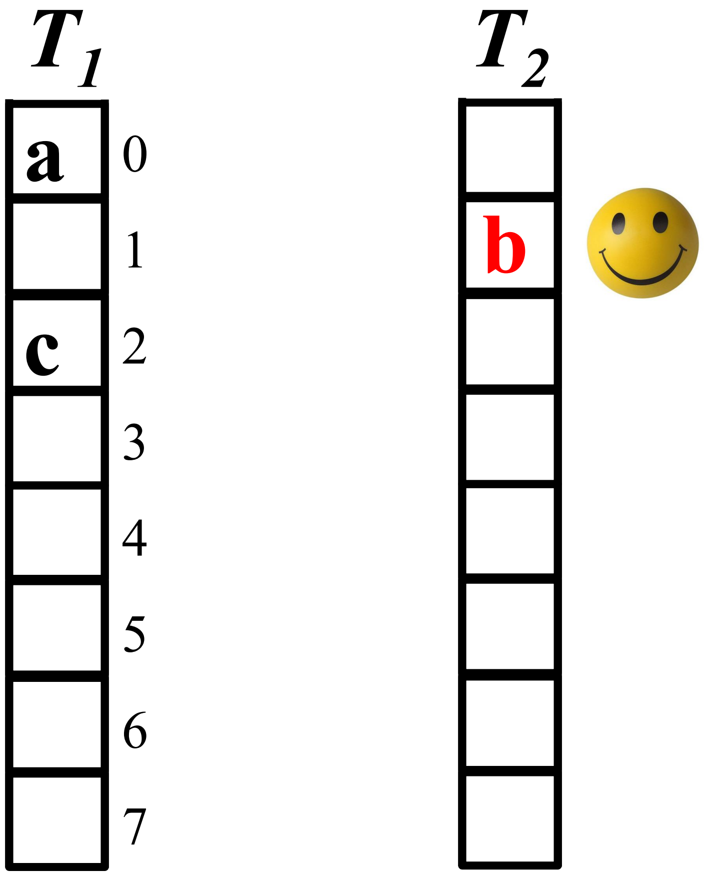

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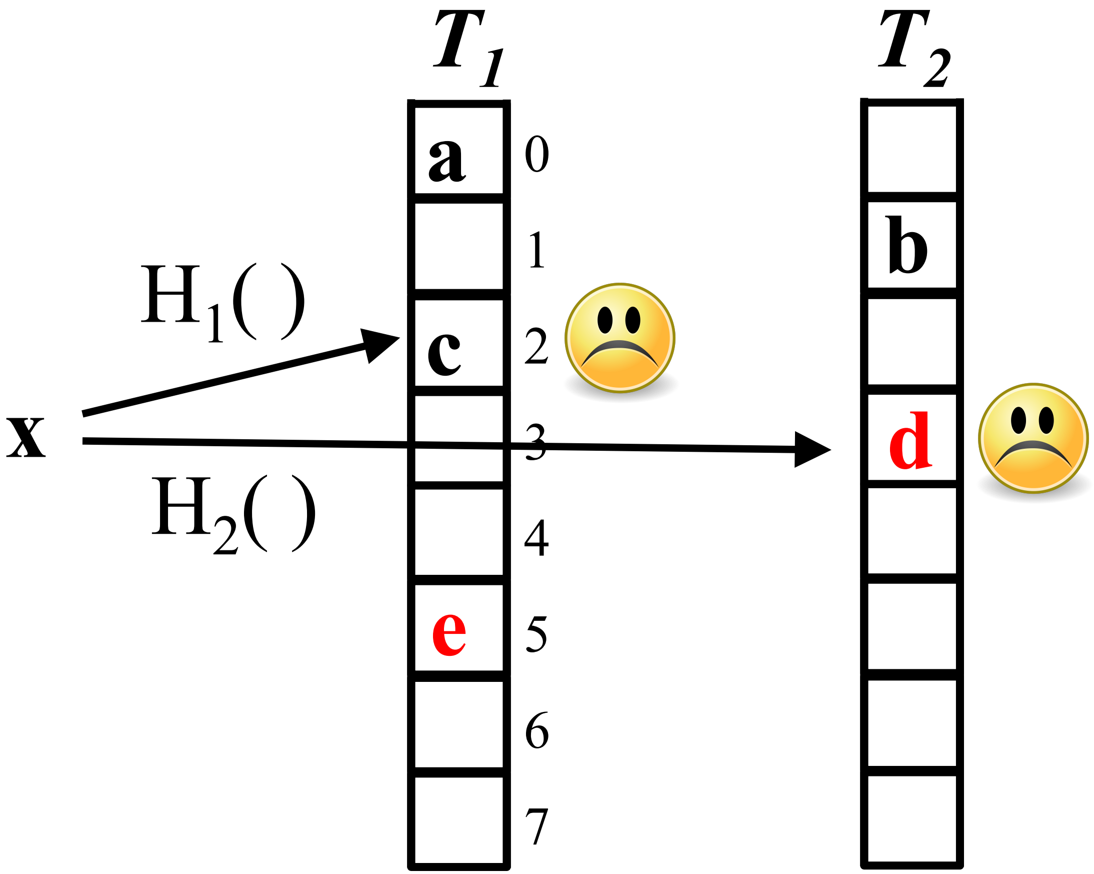

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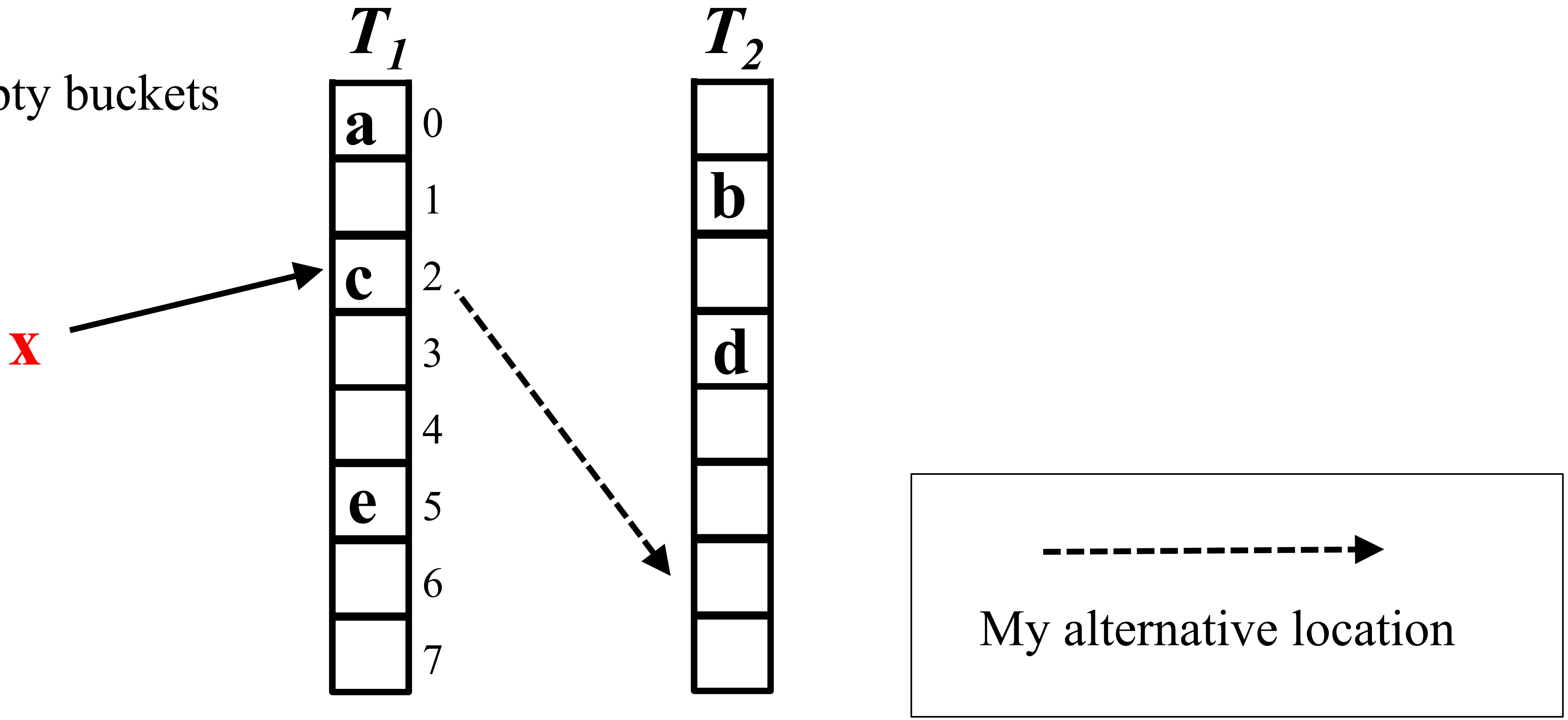
Kickout for empty buckets



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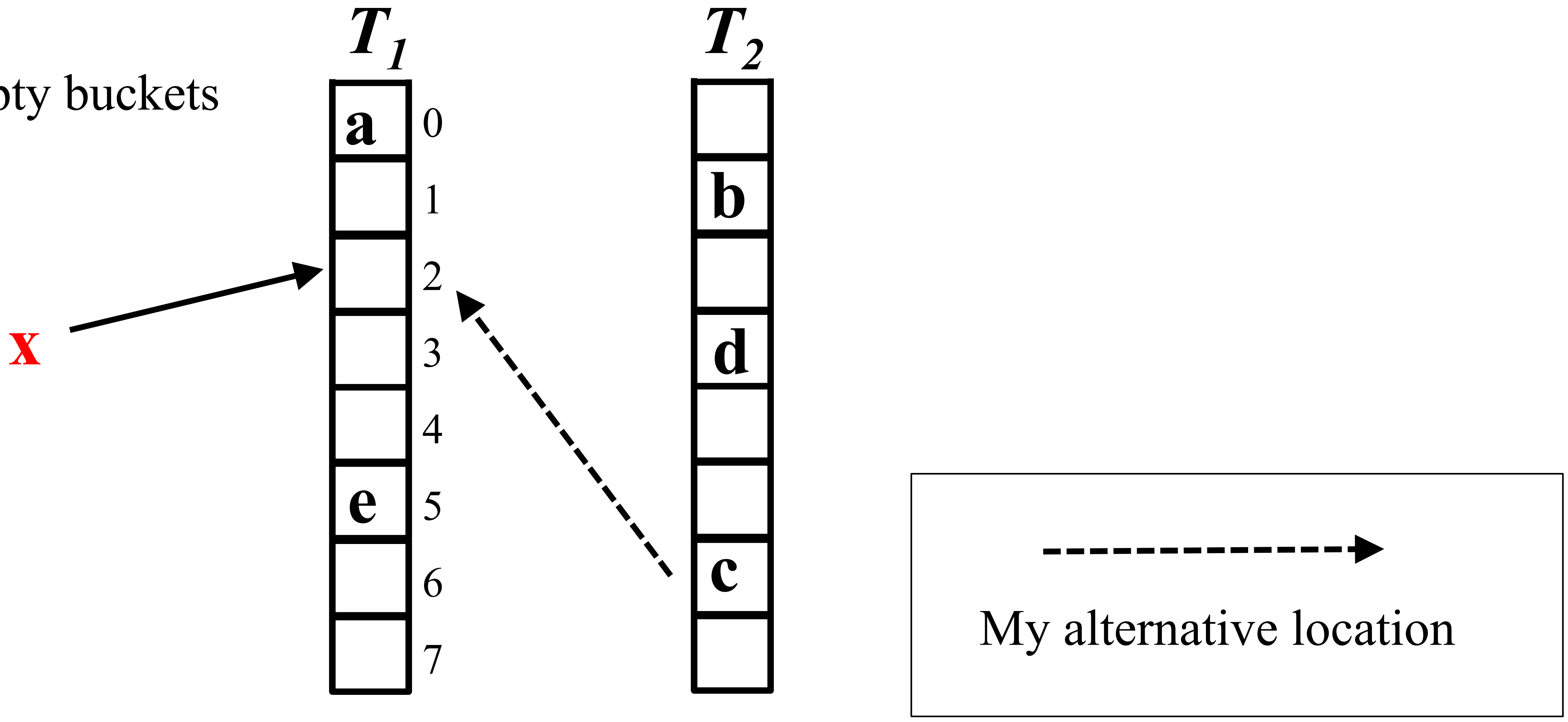

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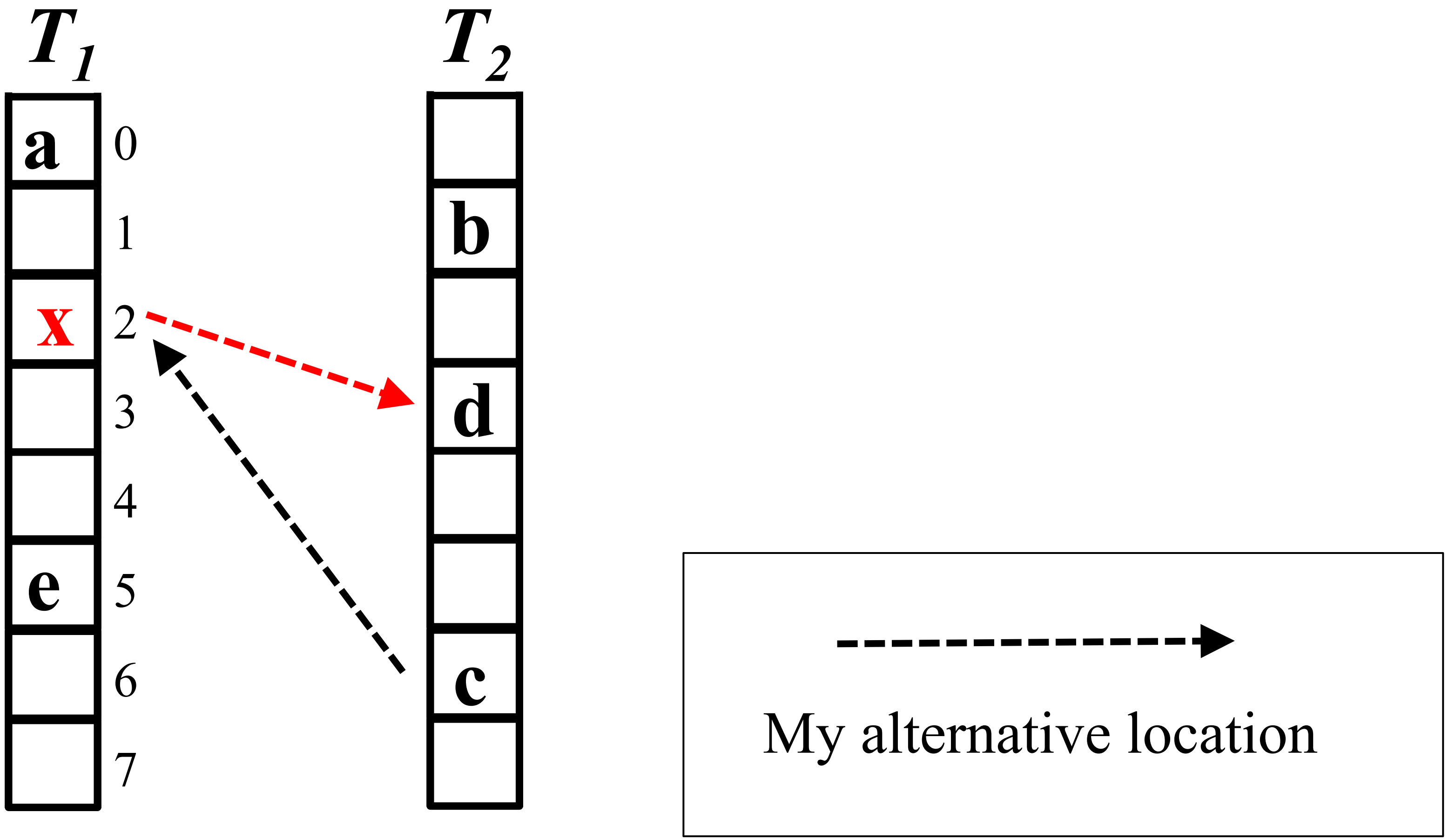

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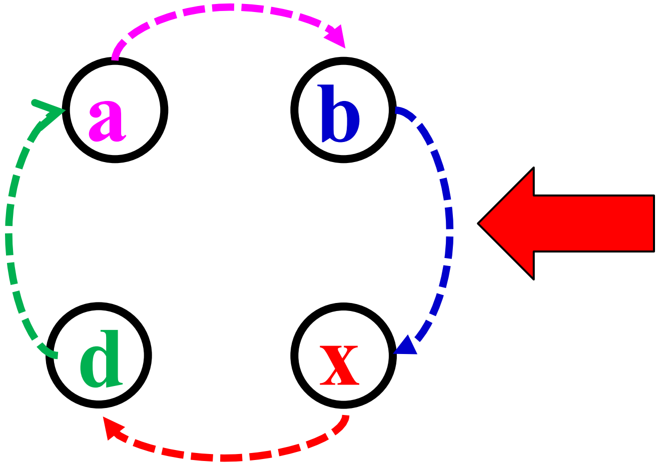
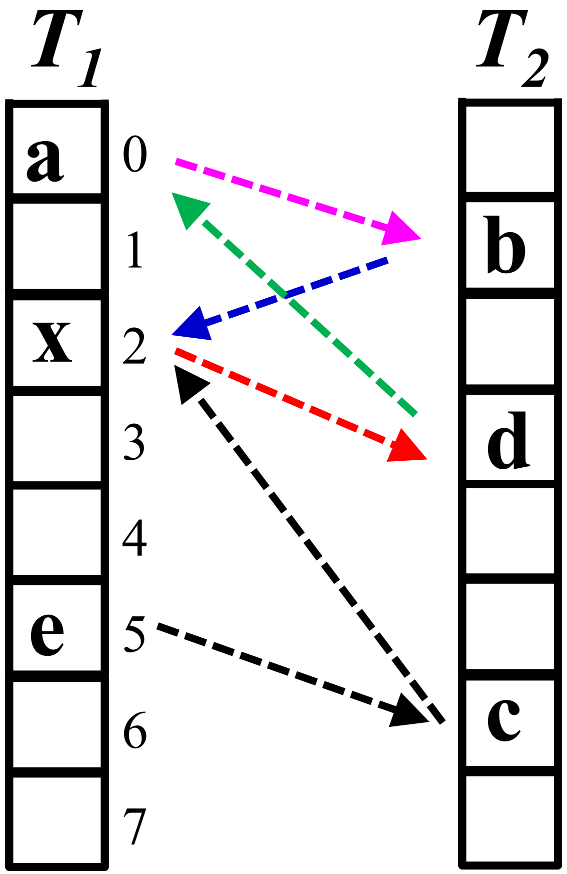
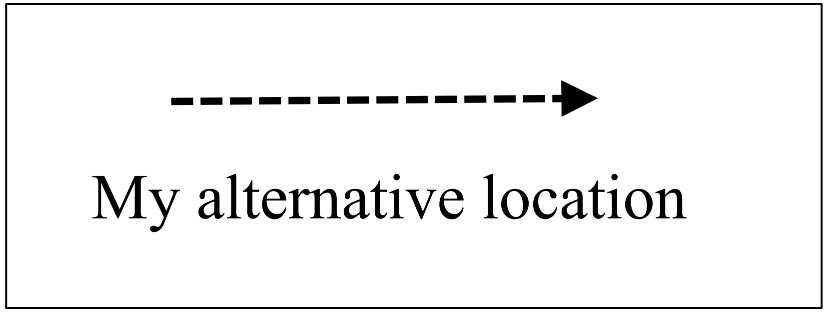


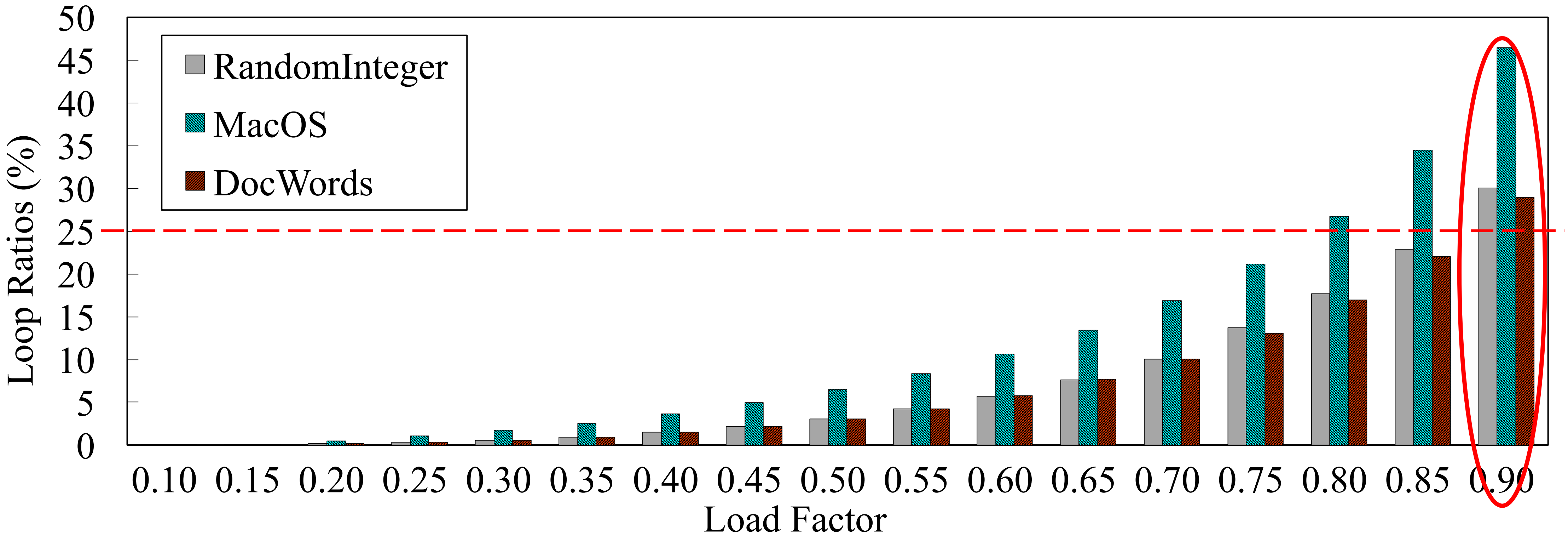


- An **endless loop** is formed.
- **Endless kickouts** for any insertion within the loop.



Observations

- Endless loops widely exist in the Cuckoo hashing structures.
  - More than 25% (cuckoo hashing with a stash)
- Loop ratio: the percentage of insertion failures due to loops



Existing works

- ChunkStash @USENIX ATC'10
  - Collisions: resursive strategy to relocate one of keys in candidates
  - Loops: an auxiliary linked list (or, hash table)

- MemC3 @NSDI'13
  - Collisions: random and repeat relocation (500 times)
  - Loops: an expansion process
  - Stand-alone implementation: libcuckoo @ EuroSys'14

- Horton tables @USENIX ATC'16
  - Recursively evicting keys within a certain search tree height

Motivations

- Due to endless loops:
  - Substantial resources consumption
    - A large number of step-by-step kick-out operations
  - Unbounded performance
    - Fruitless effort

- Design Goal:
  - Predetermining and avoiding occurrence of endless loops

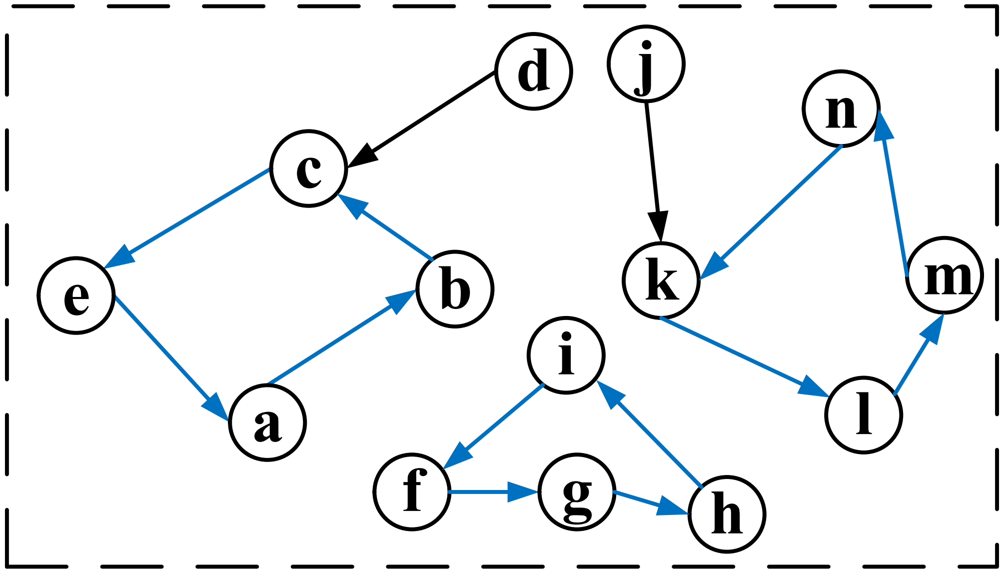
Our approach: SmartCuckoo

- Tracking item placements in the hash table
  - Representing the hashing relationship as a directed pseudoforest
  - Classifying item insertions into three cases
  - **Predetermining and avoiding loops** during insertion without any kick-out attempts.

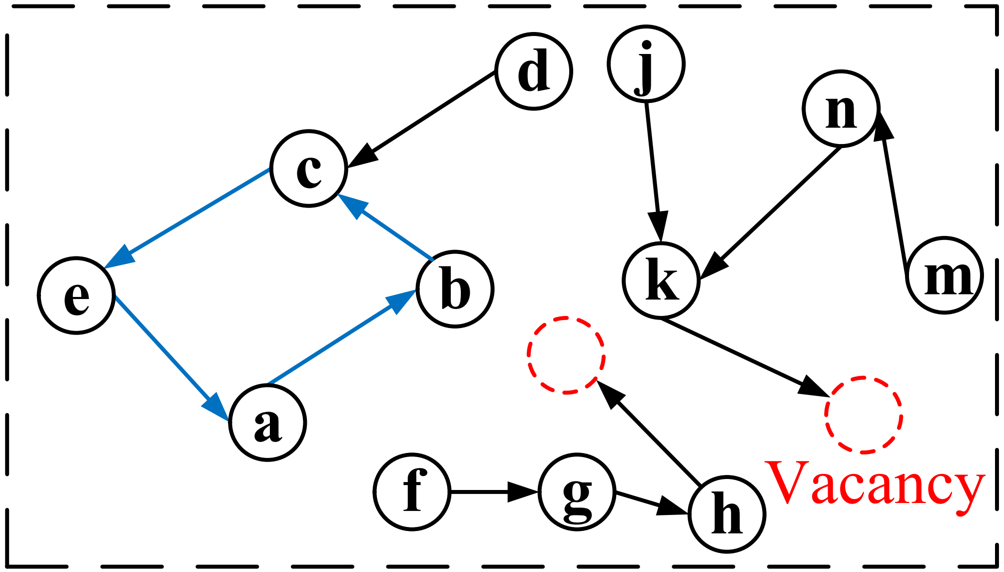
How to identify loop(s)?

- Pseudoforest:
  - A graph: each vertex has an outdegree of at most one
  - Each connected component (subgraph) has at most one cycle (loop)
  - In a subgraph:

Loop ⟷ #Vertices = #Edges **No loop ⟷ #Vertices = #Edges + 1**



Maximal



Non-maximal

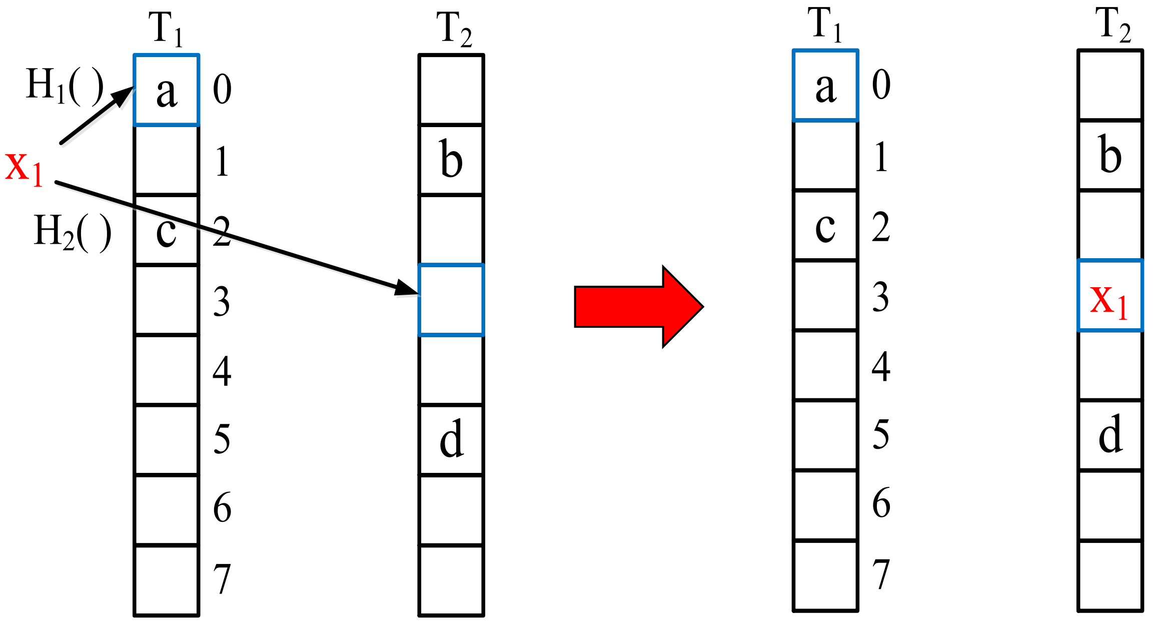
Classification and predetermination

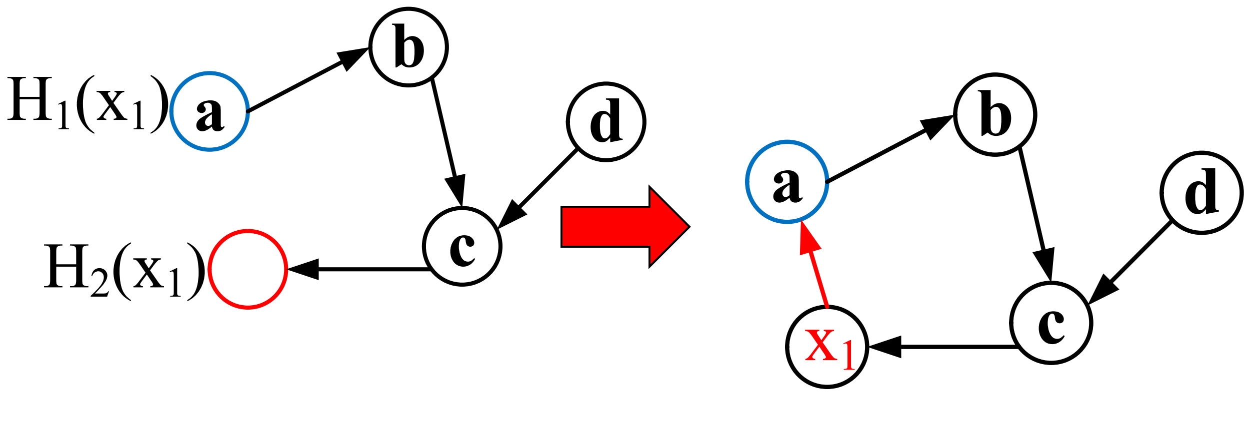
- Three cases depending on the number of vertices added to the graph
  - v+0, v+1, and v+2
  - v+0: 5 possible scenarios based on the status of corresponding subgraph(s)

Three cases	v+0					v+1	v+2
Two insert positions of a key	Same subgraph		Different subgraphs			A new one	Two new ones
Subgraph status	Non-maximal	Maximal	Both non-maximal	A maximal and a non-maximal	Both maximal	-	-
Scenarios	(a)	(e)	(b)	(c)	(d)	-	-

v+0: (a) One non-maximal subgraph

- One empty bucket
- Success!

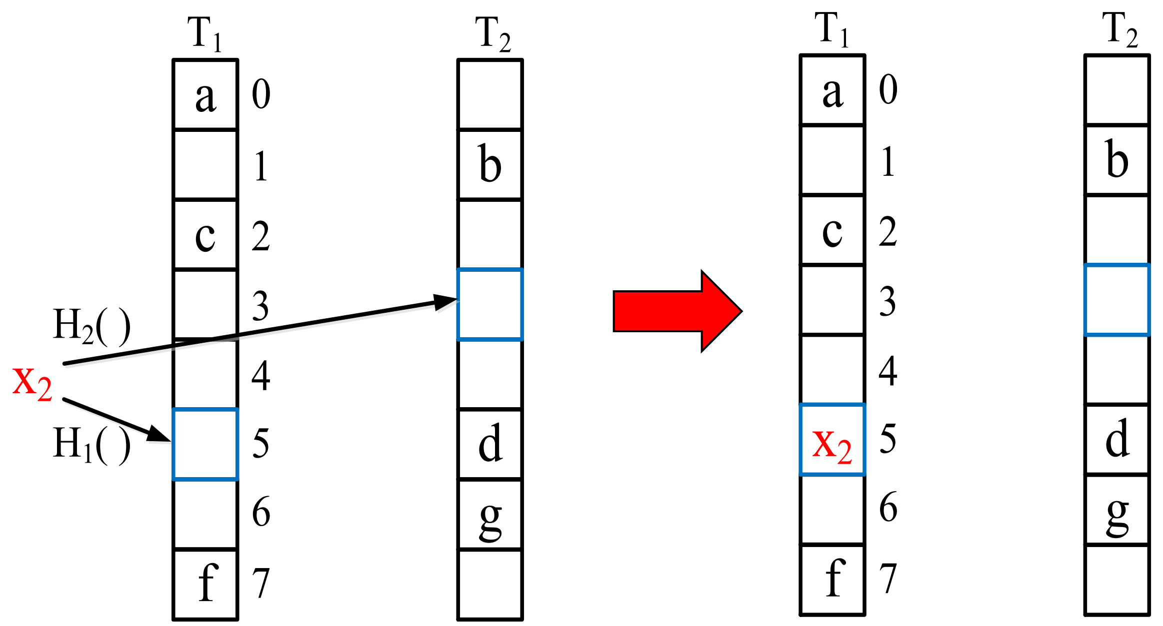


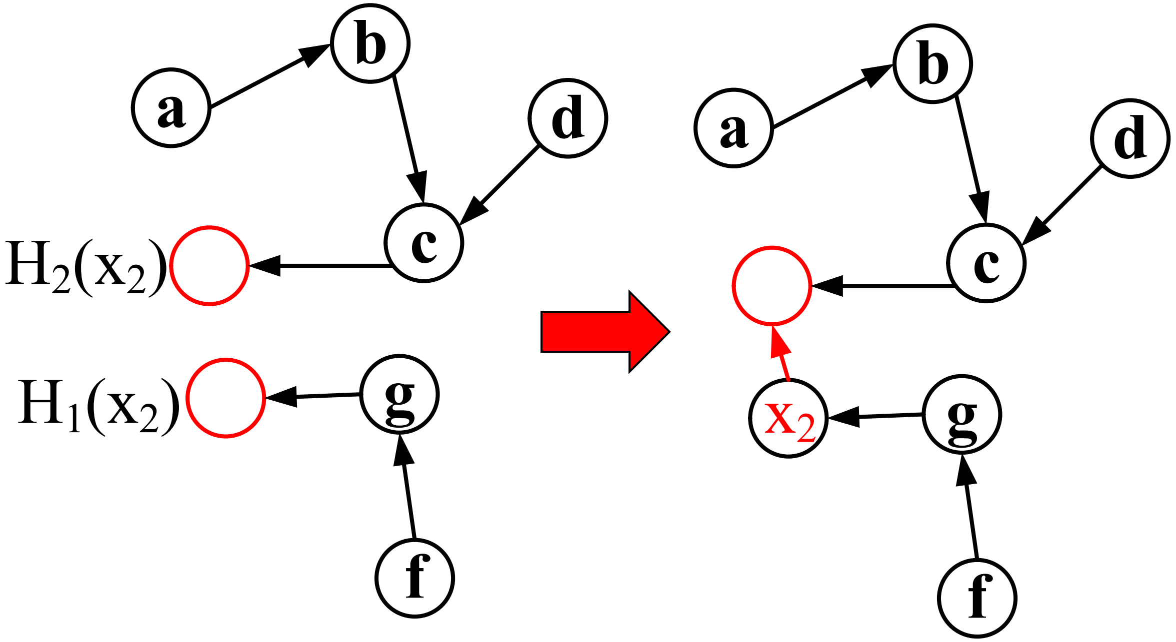


Pseudoforest

v+0: (b) Two non-maximal subgraphs

- Two empty buckets
- Success!

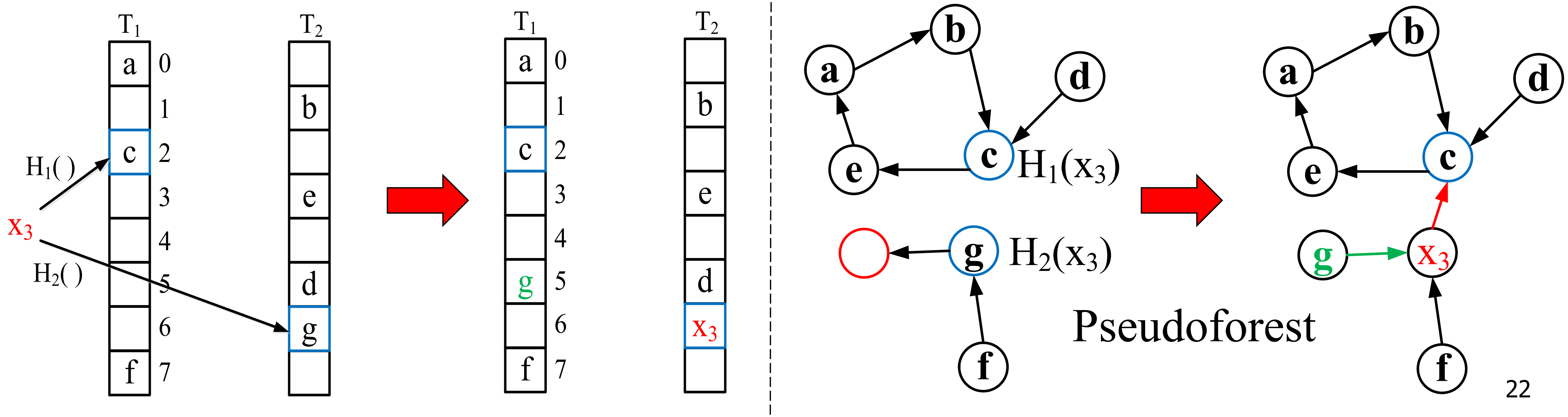




Pseudoforest

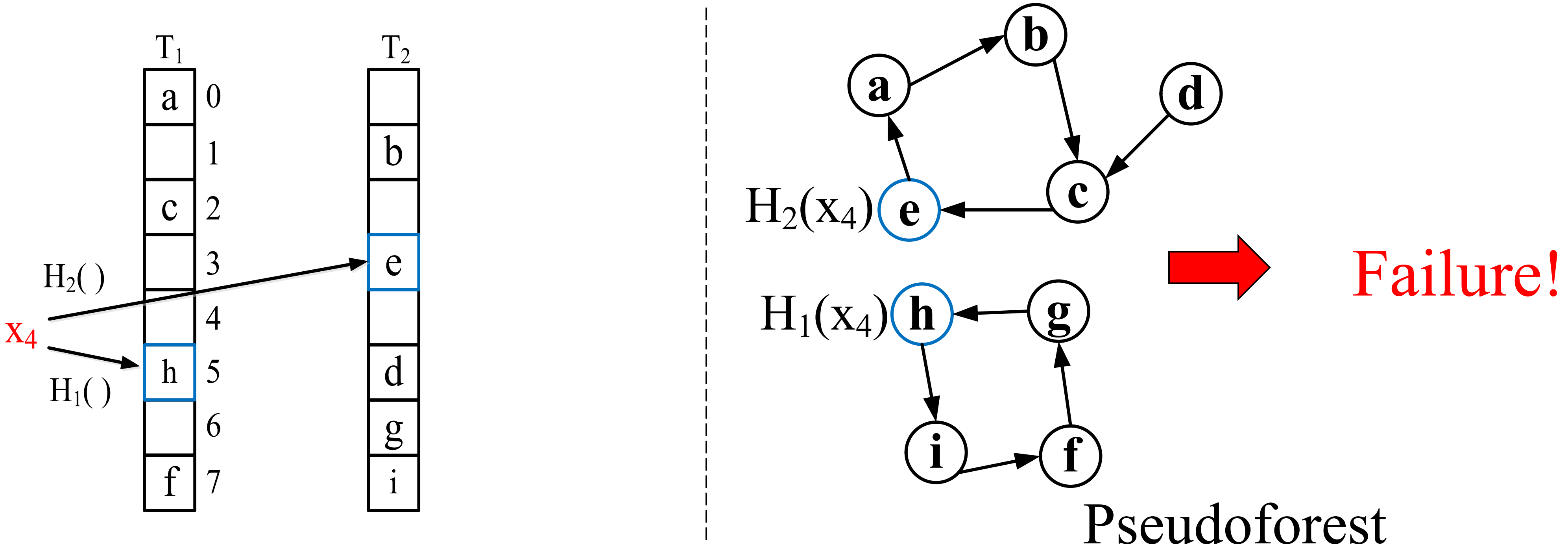
v+0: (c) One maximal and one non-maximal

- One loop and one empty bucket
- Conventional cuckoo hashing: taking a random walk
  - T_1: executing extra useless kick-out operations
  - T_2: making a success
  - SmartCuckoo: directly selecting to enter from T_2
- Success!



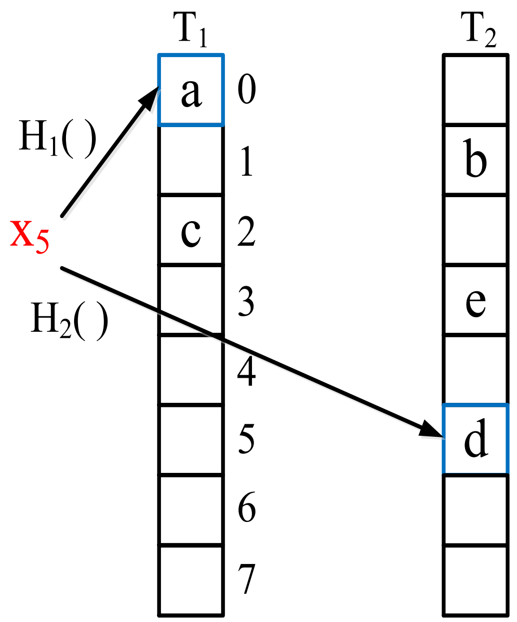
v+0: (d) Two maximal subgraphs

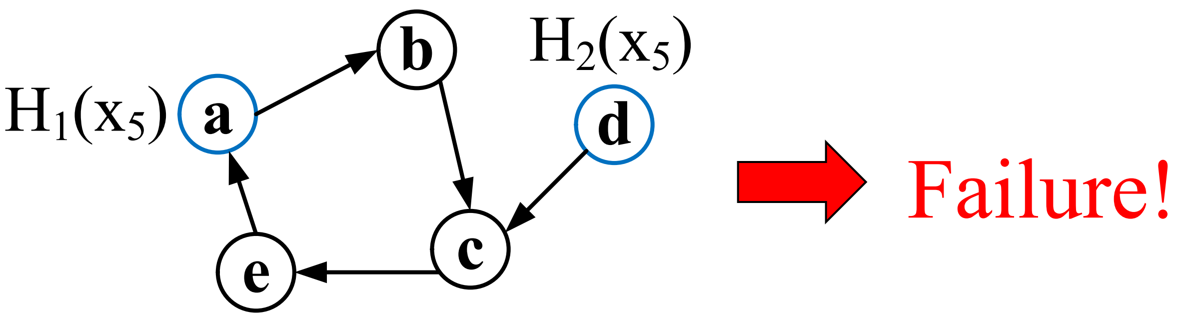
- Two loops!
- Execution:
  - Conventional cuckoo hashing: sufficient attempts, then reporting a failure
  - SmartCuckoo: reporting a failure without any kick-out operations.



v+0: (e) One maximal subgraph

- One loop!

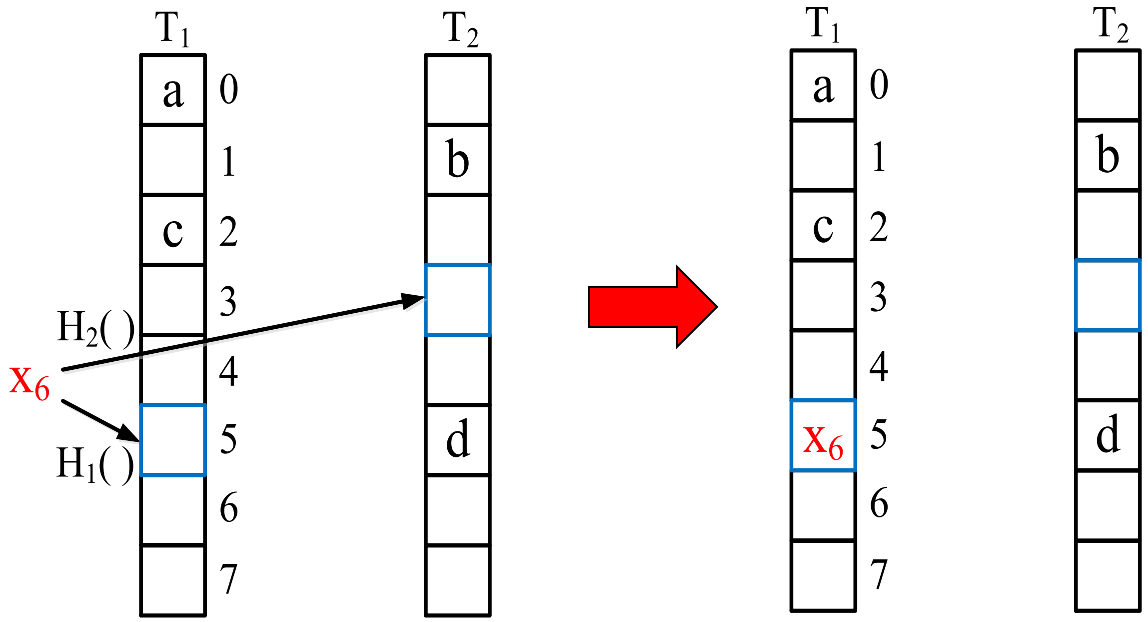


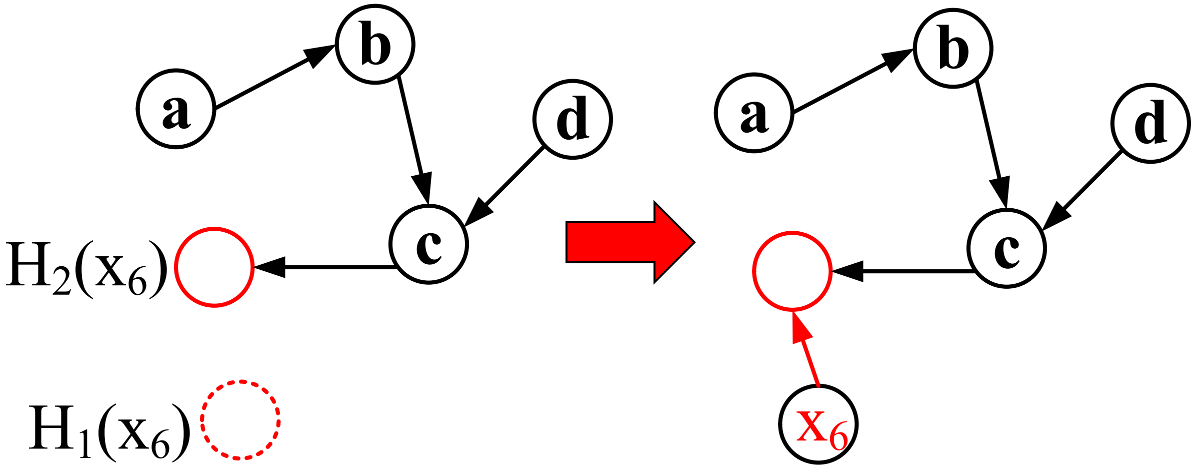


Pseudoforest

Case: v+1

- A new vertex after the item's insertion
- Success!

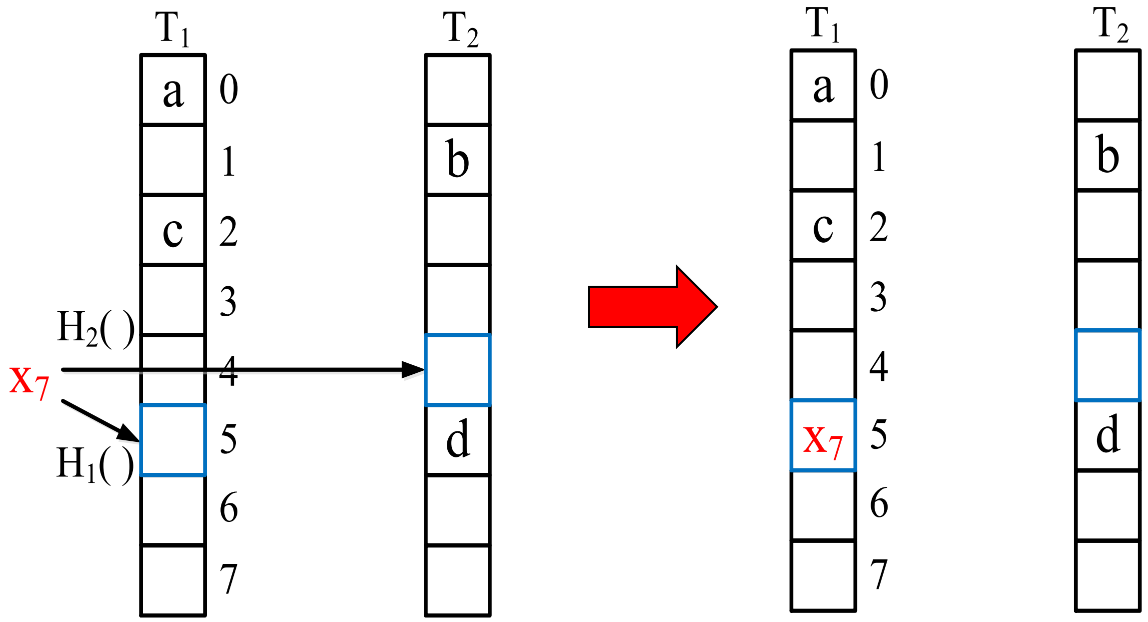


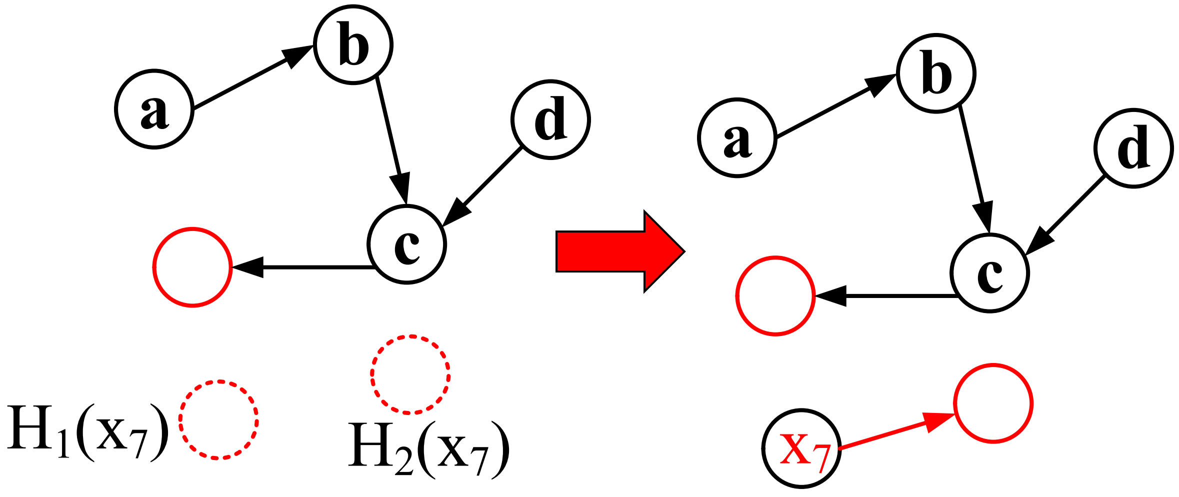


Pseudoforest

Case: v+2

- Two new vertices after the insertion
- Success!



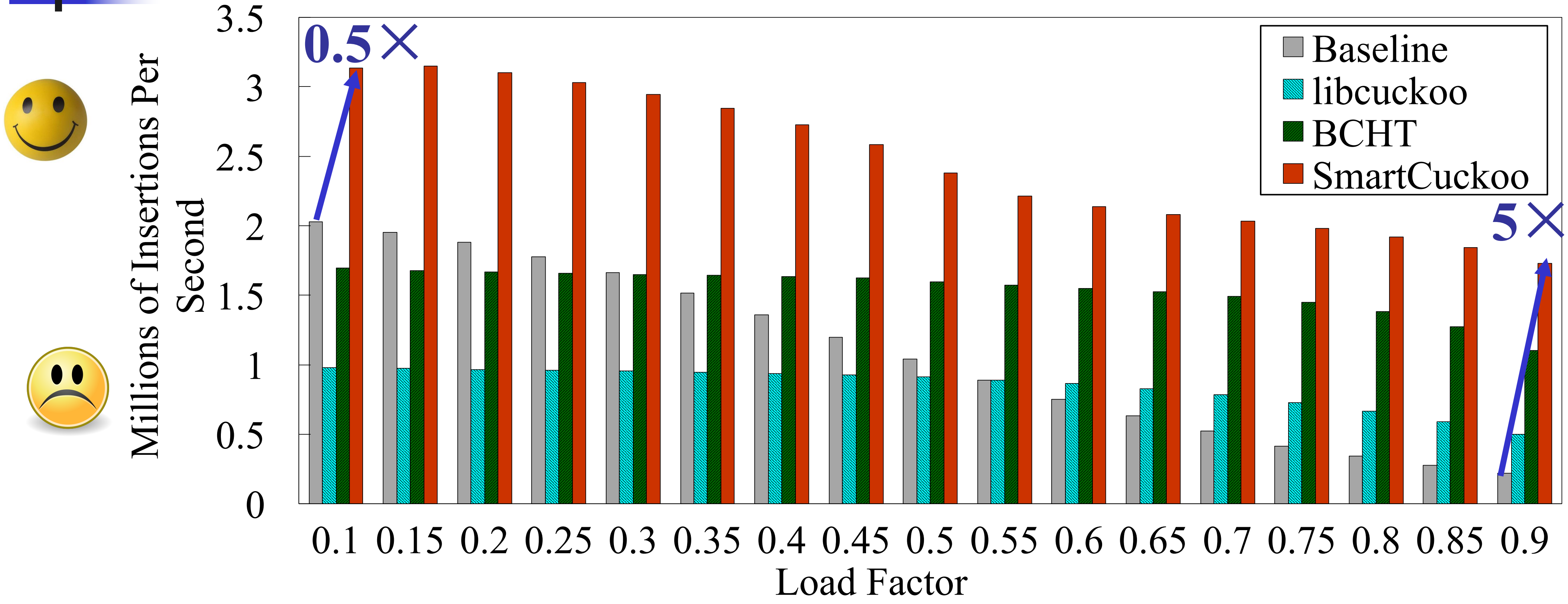


Pseudoforest

Evaluation methodology

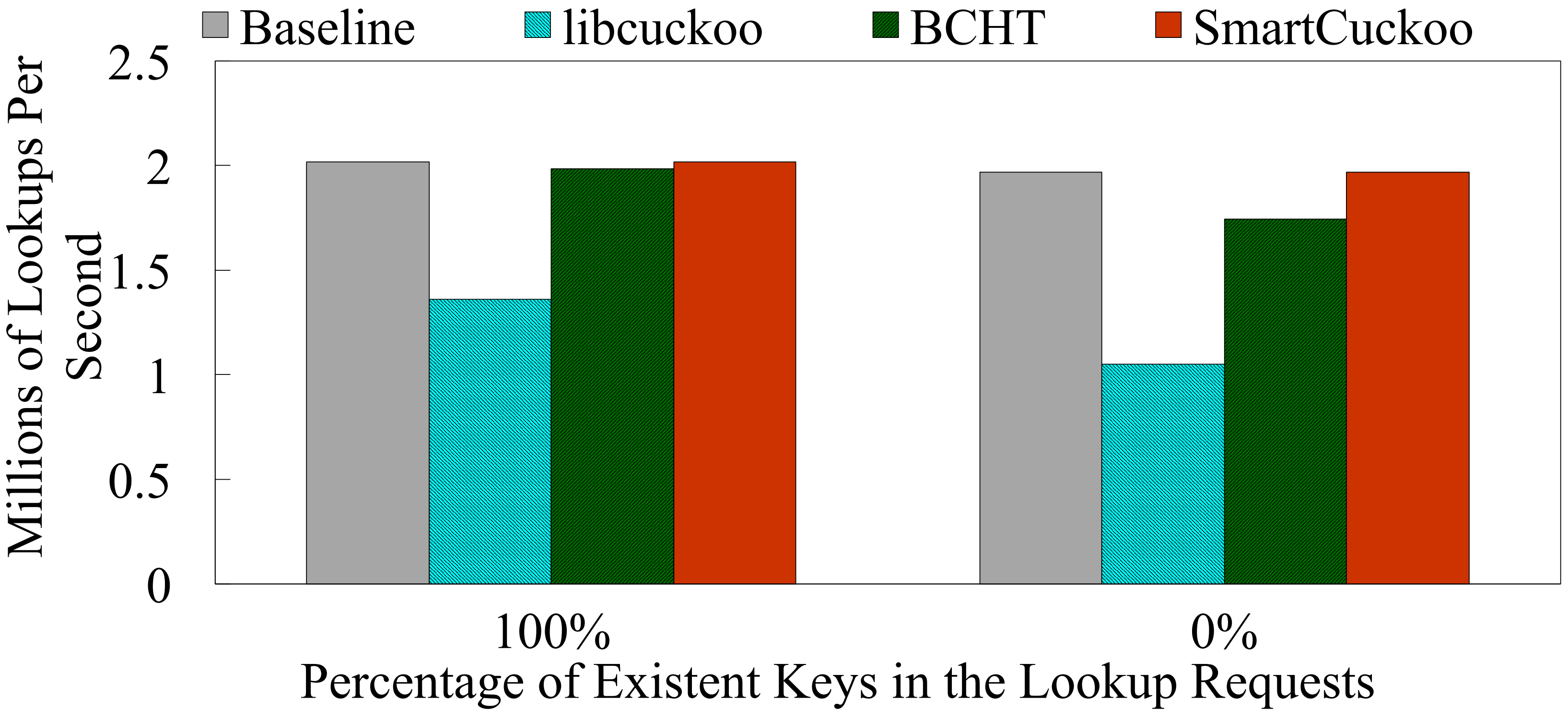
- Comparisons:
  - Baseline (Cuckoo hashing with a stash @ SIAM Journal on Computing'09)
  - libcuckoo @ EuroSys'14
  - BCHT (bucketized cuckoo hash table)
- Traces:
  - RandomInteger: random integer generator @ TOMACS'98
  - MacOS: http://tracer.filesystems.org
  - DocWords: http://archive.ics.uci.edu/ml/datasets/Bag+of+Words
  - YCSB: https://github.com/brianfrankcooper/YCSB @ SOCC'11
- Metrics: in millions of operations per second
  - Insertion throughput
  - Lookup throughput: positive/negative
  - Throughput of workload with mixed queries (YCSB)

Insertion throughput



- SmartCuckoo significantly increases insertion throughputs.
- 0.5× to 5× speedups compared to Baseline.

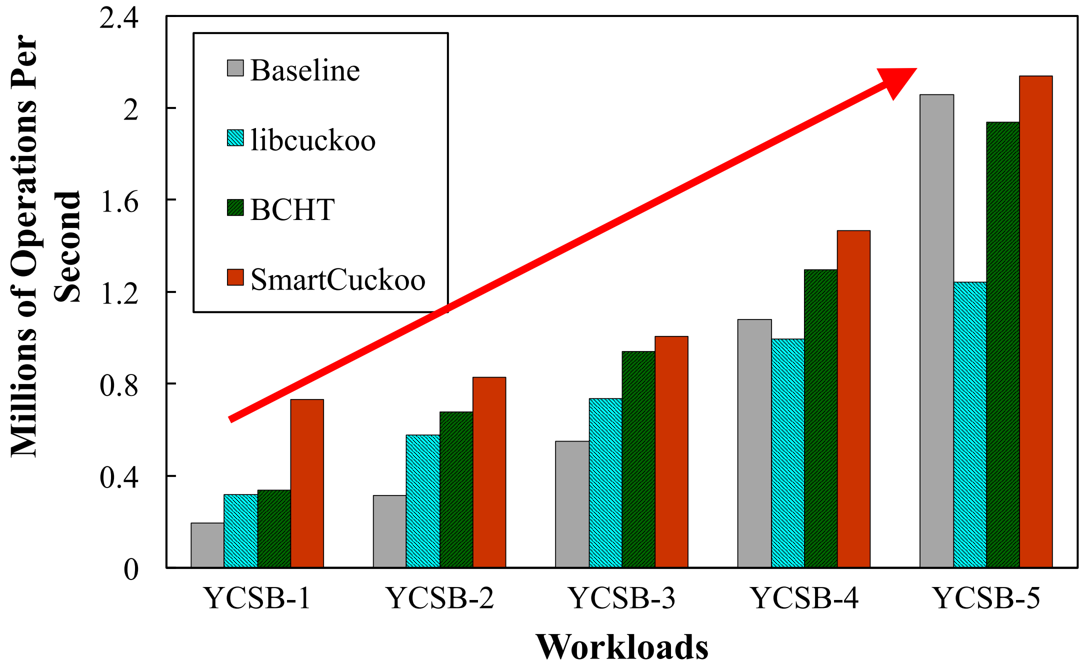
Lookup throughput



- 0%: all candidate positions for a key have to be accessed.
- Almost the same lookup throughput with Baseline.
- Significantly higher than libcuckoo and BCHT.

Throughput of workload with mixed queries

Workload	Insert	Lookup	Update
YCSB-1	100	0	0
YCSB-2	75	25	0
YCSB-3	50	50	0
YCSB-4	25	75	0
YCSB-5	0	95	5



- With the decrease of the percentage of insertions, all schemes increase the throughputs.
- In each workload, SmartCuckoo produces higher throughput than other three schemes.

Conclusion and future work

- Cuckoo hashing is cost-efficient to offer O(1) query performance.
- We address the problem of potential endless loops in item insertion.
- SmartCuckoo helps improve predictable performance in storage systems.

- To-do-list:
  - SmartCuckoo in hash tables with more than two hash functions;
  - The use of multiple slots in each bucket.

Thanks and questions?

Open-source code: https://github.com/syy804123097/SmartCuckoo