Cuckoo Filter: Practically Better Than Bloom

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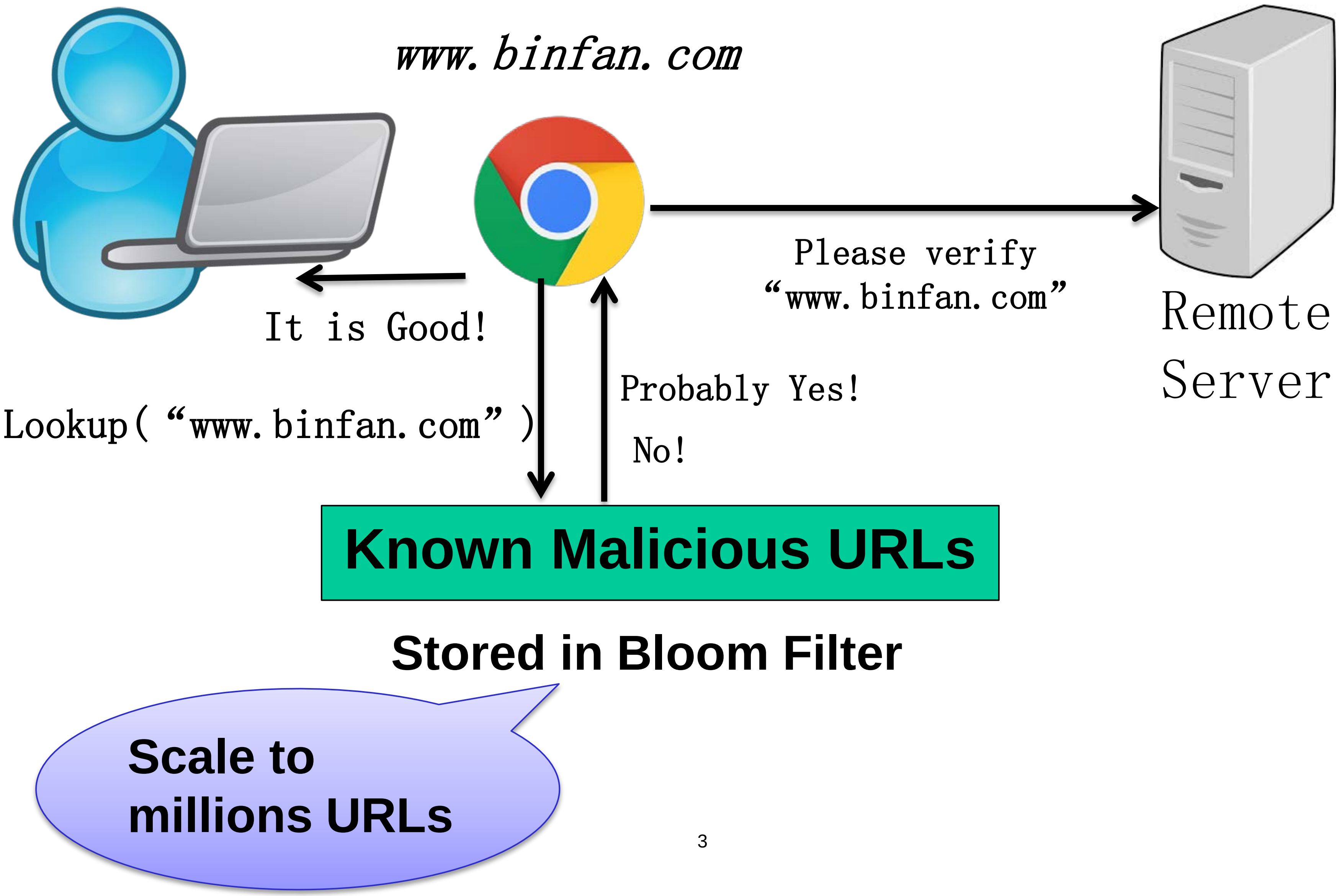
What is Bloom Filter? A Compact Data Structure Storing Set-membership

- Bloom Filters answer "is item ***x*** in set ***Y*** " by:
  - "**definitely no**", or
  - "**probably yes**" with probability ***ε*** to be wrong

false positive rate

- Benefit: not always precise but highly compact
  - Typically a few bits per item
  - Achieving lower ***ε*** (more accurate) requires spending more bits per item

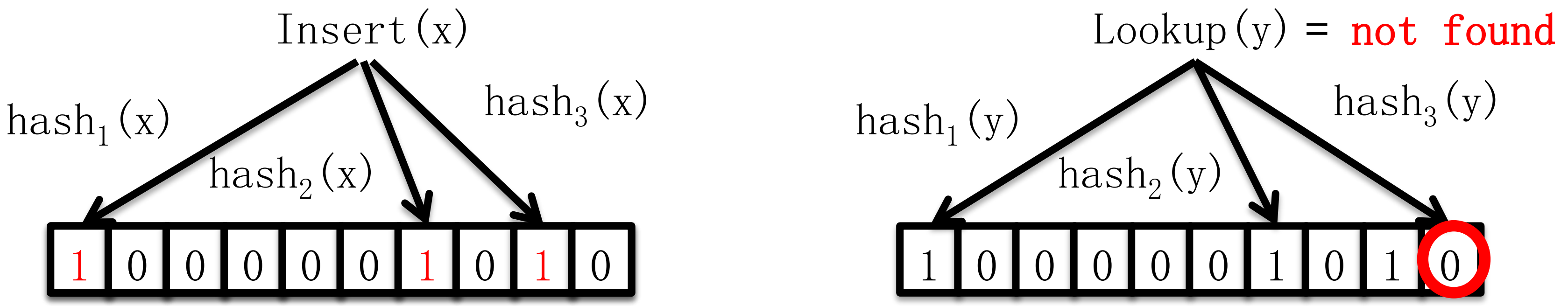
Example Use: Safe Browsing



Bloom Filter Basics

A Bloom Filter consists of ***m*** bits and ***k*** hash functions

Example: ***m*** = 10, ***k*** = 3



Succinct Data Structures for Approximate Set-membership Tests

	High Performance	Low Space Cost	Delete Support
Bloom Filter	✔	✔	✗
Counting Bloom Filter	✔	✗	✔
Quotient Filter	✗	✔	✔

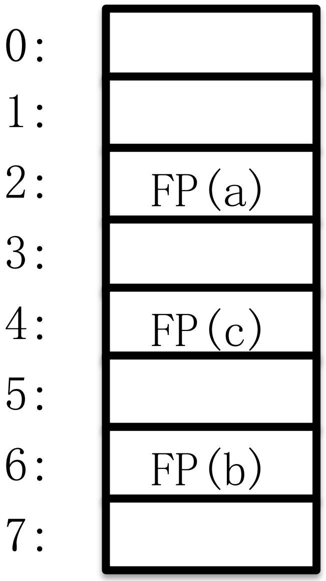
Can we achieve all three in practice?

Outline

- Background
- **Cuckoo filter algorithm**
- Performance evaluation
- Summary

Basic Idea: Store Fingerprints in Hash Table

- **Fingerprint**(x): A hash value of x
  - Lower false positive rate ε, longer fingerprint



Basic Idea: Store Fingerprints in Hash Table

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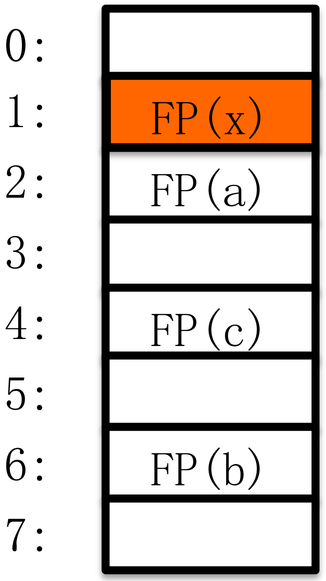
- **Insert**(x):
  - add **Fingerprint(x)** to hash table



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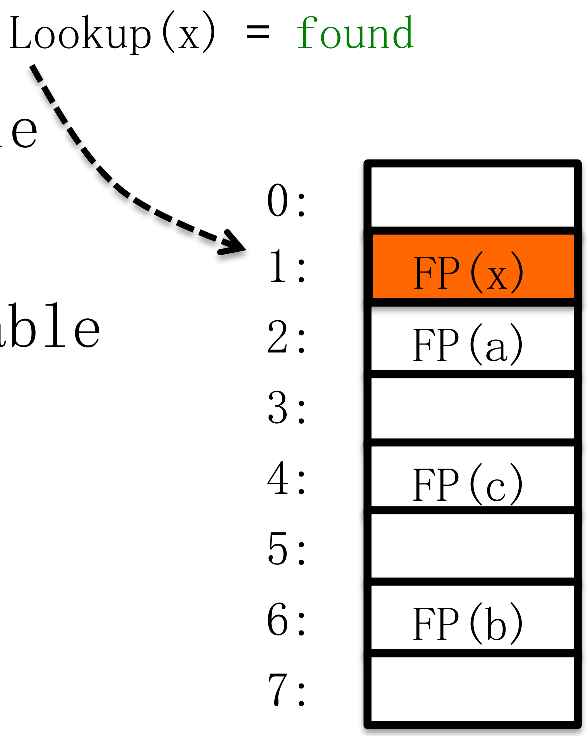

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- **Lookup**(x):
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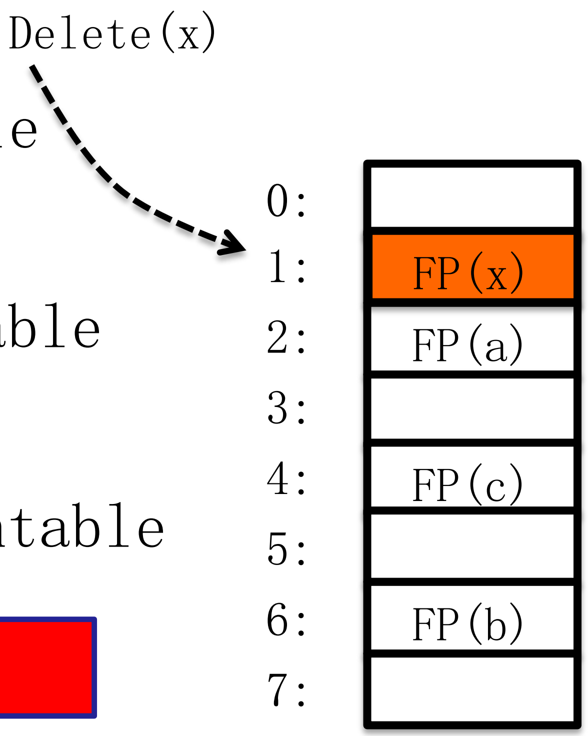
- **Delete**(x):
  - remove **Fingerprint**(x) from hashtable

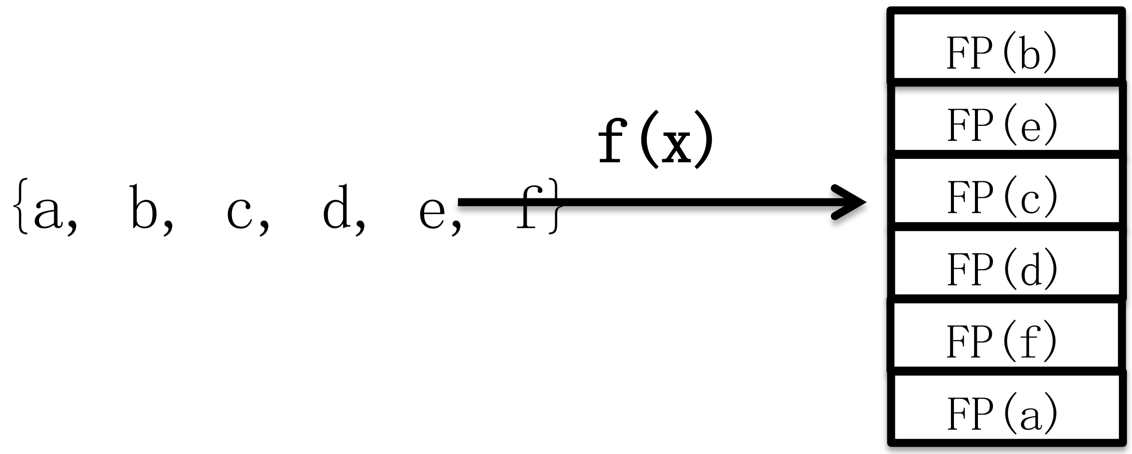


How to Construct Hashtable?

Strawman

(Minimal) Perfect Hashing: No Collision but Update is Expensive

- Perfect hashing: maps all items with no collisions



Strawman

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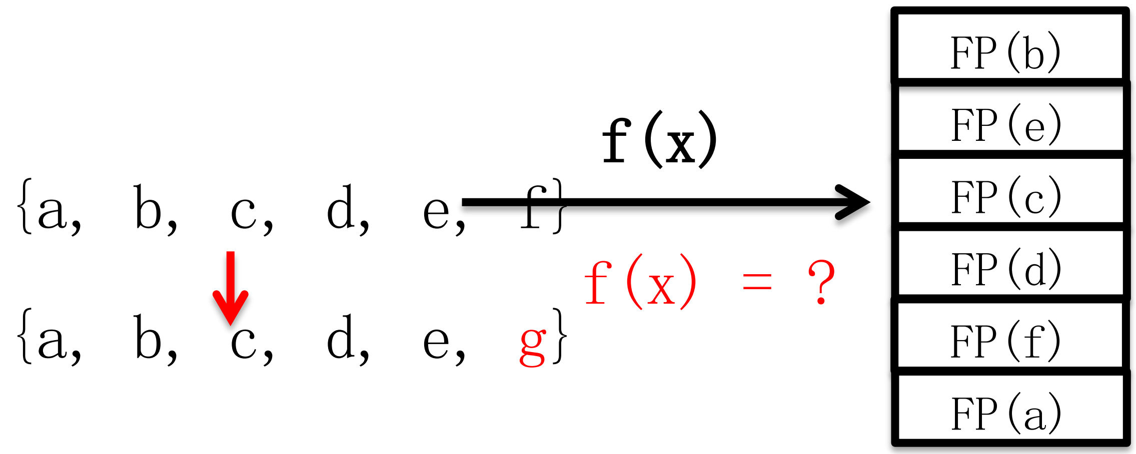
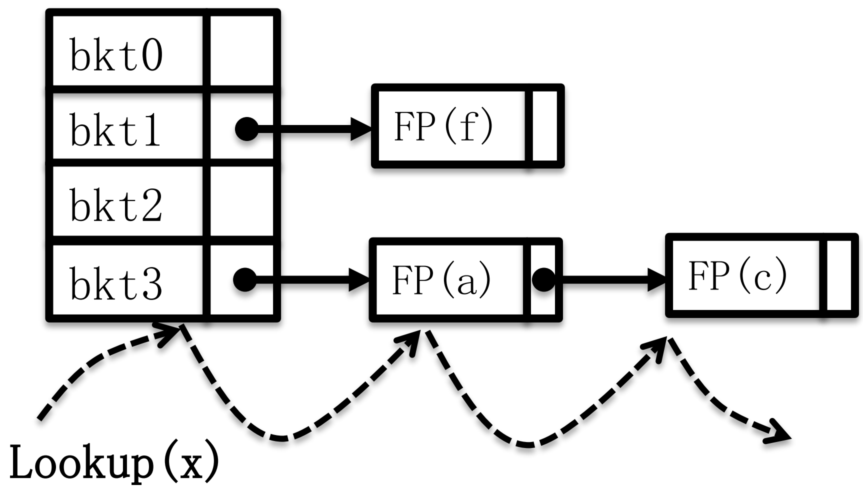


- Changing set must recalculate f ➔ high cost/bad performance of update

Strawman

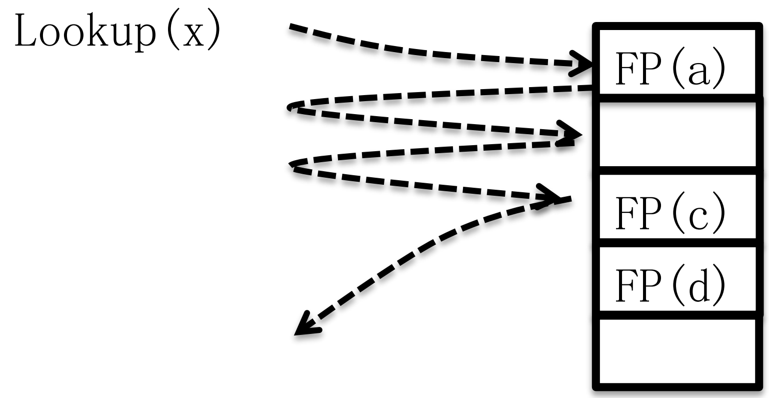
Convention Hash Table: High Space Cost

- Chaining :



- Pointers ➔
  low space utilization

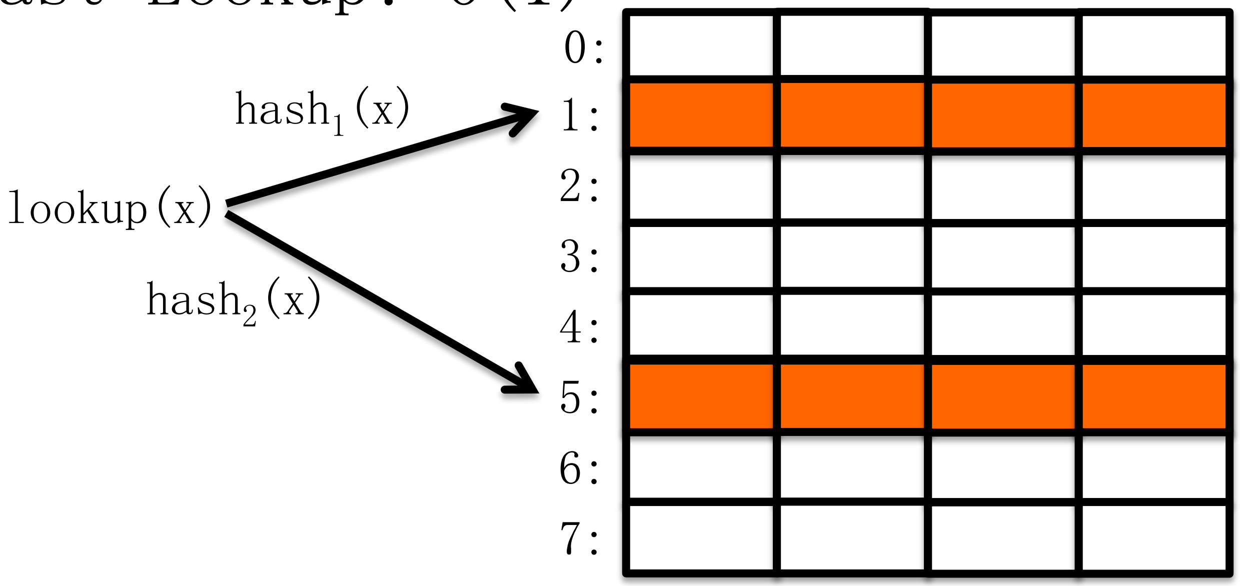
- Linear Probing



- Making lookups O(1) requires large % table empty ➔
  low space utilization
- Compare multiple fingerprints sequentially ➔
  more false positives

Cuckoo Hashing[Pagh2004] Good But ..

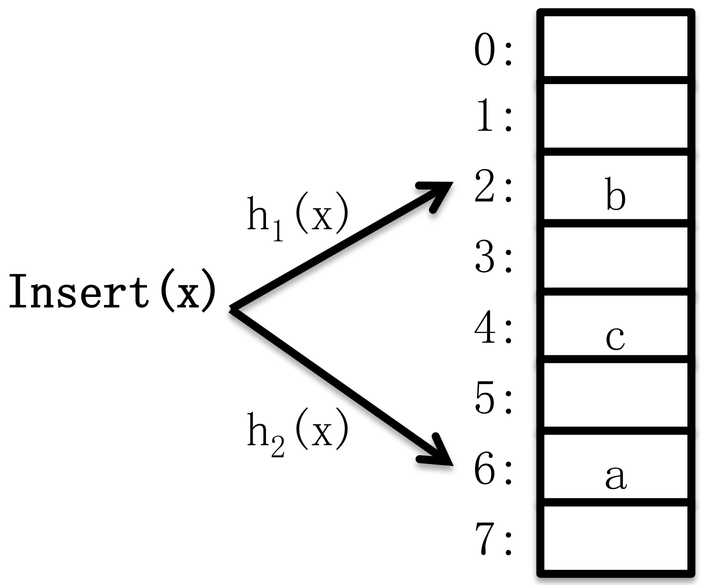
- High Space Utilization
  - 4-way set-associative table: >95% entries occupied
- Fast Lookup: O(1)



Standard cuckoo hashing doesn't work with

[Pagh2004] Cuckoo hashing.

Standard Cuckoo Requires Storing Each Item



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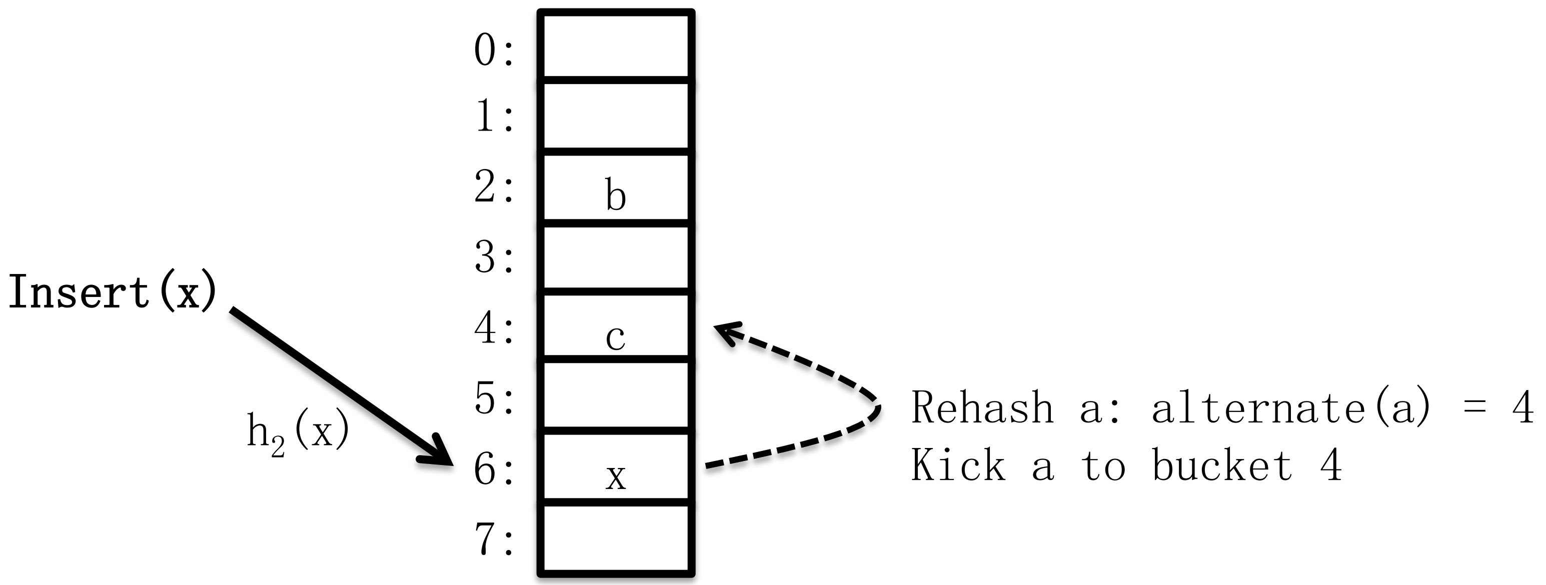

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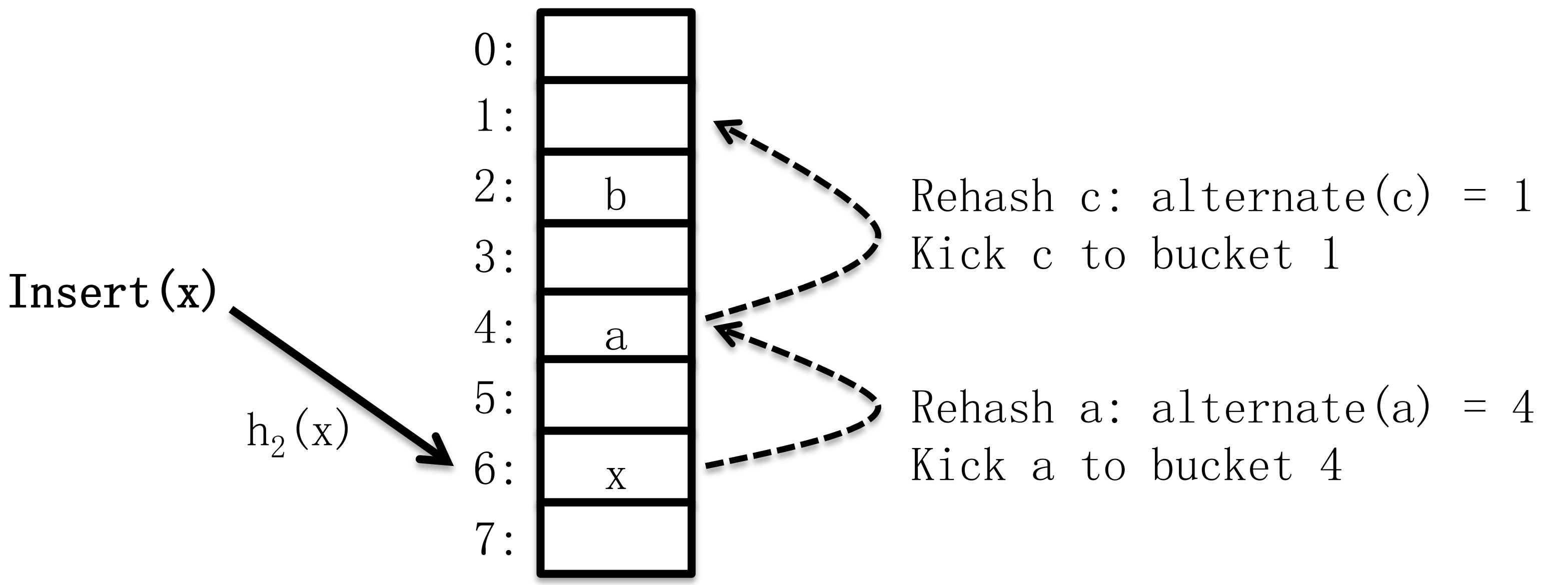

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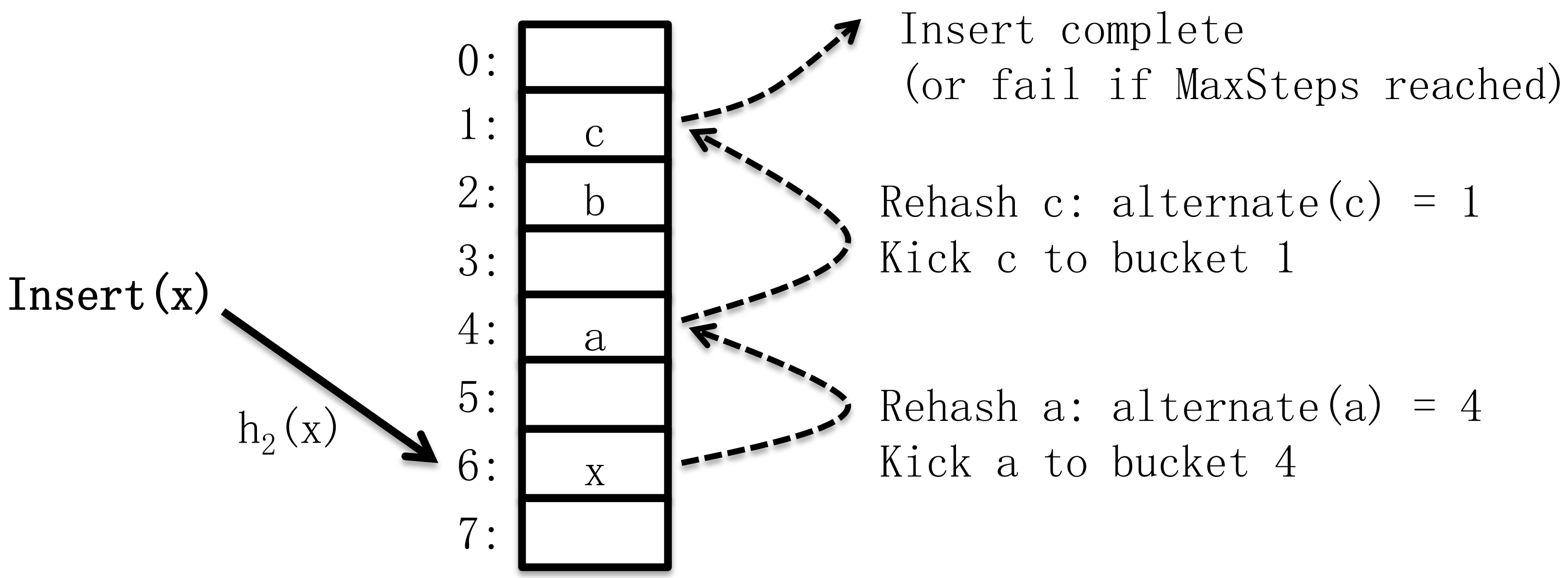
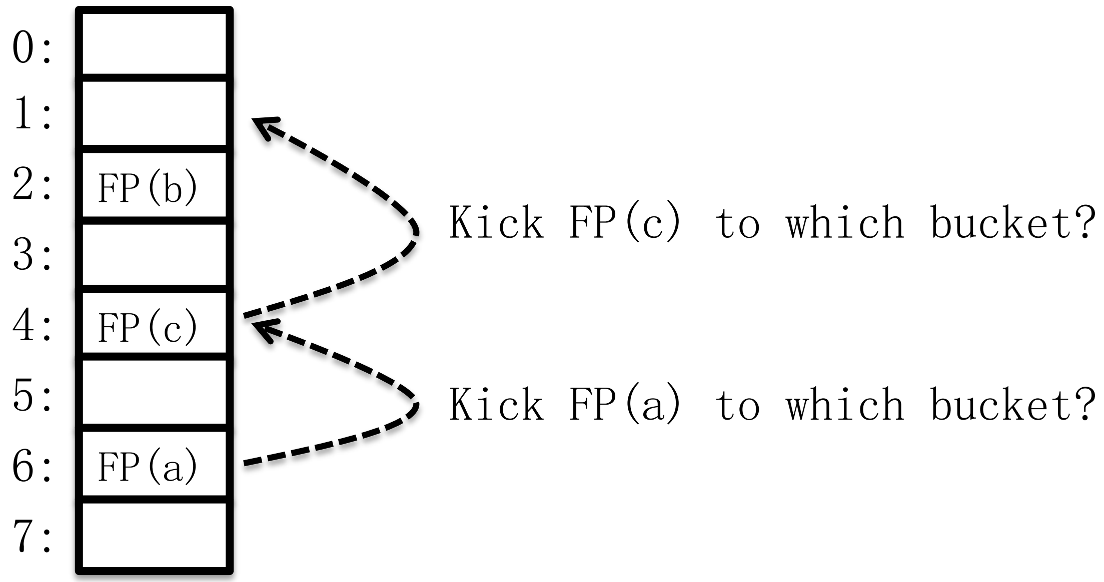


Challenge: How to Perform Cuckoo?

- Cuckoo hashing requires rehashing and displacing existing items



With only fingerprint, how to calculate item's alternate

Solution

We Apply Partial-Key Cuckoo

- Standard Cuckoo Hashing: **two independent hash functions for two buckets**

  $bucket1 = hash_1(x)$

  $bucket2 = hash_2(x)$

- Partial-key Cuckoo Hashing: **use one bucket and fingerprint to derive the other** [Fan2013]

  $bucket1 = hash(x)$

  $bucket2 = bucket1 \oplus hash(FP(x))$

To displace existing fingerprint:

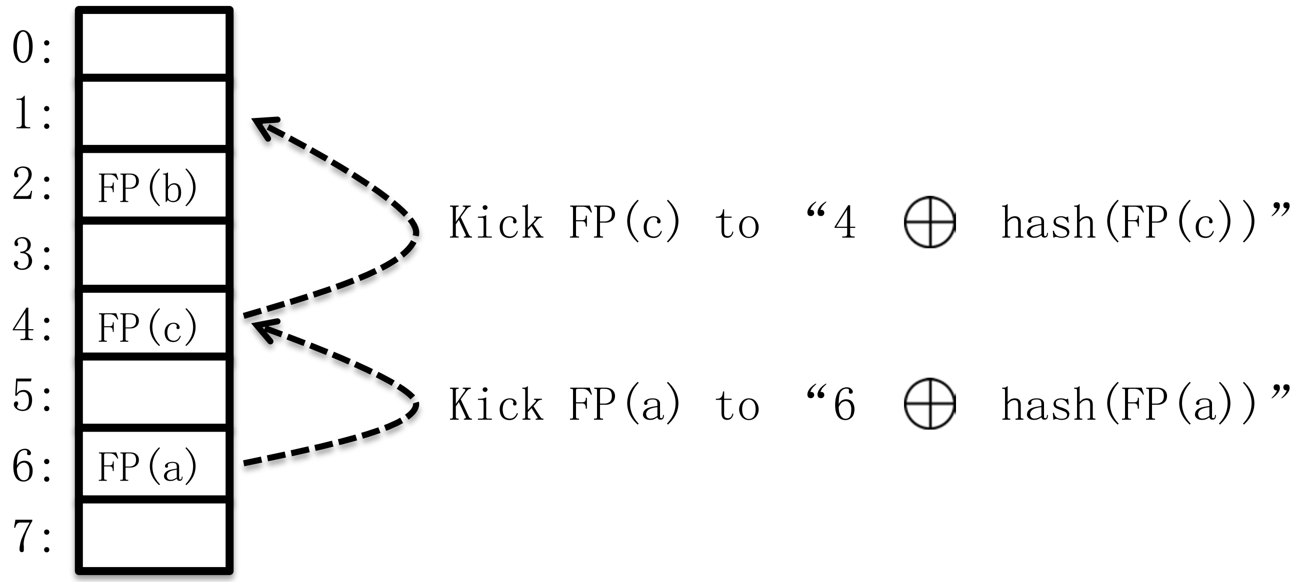
$$alternate(x) = current(x) \oplus hash(FP(x))$$

[Fan2013] MemC3: Compact and Concurrent MemCache with Dumber Caching and Smarter Hashing

Solution

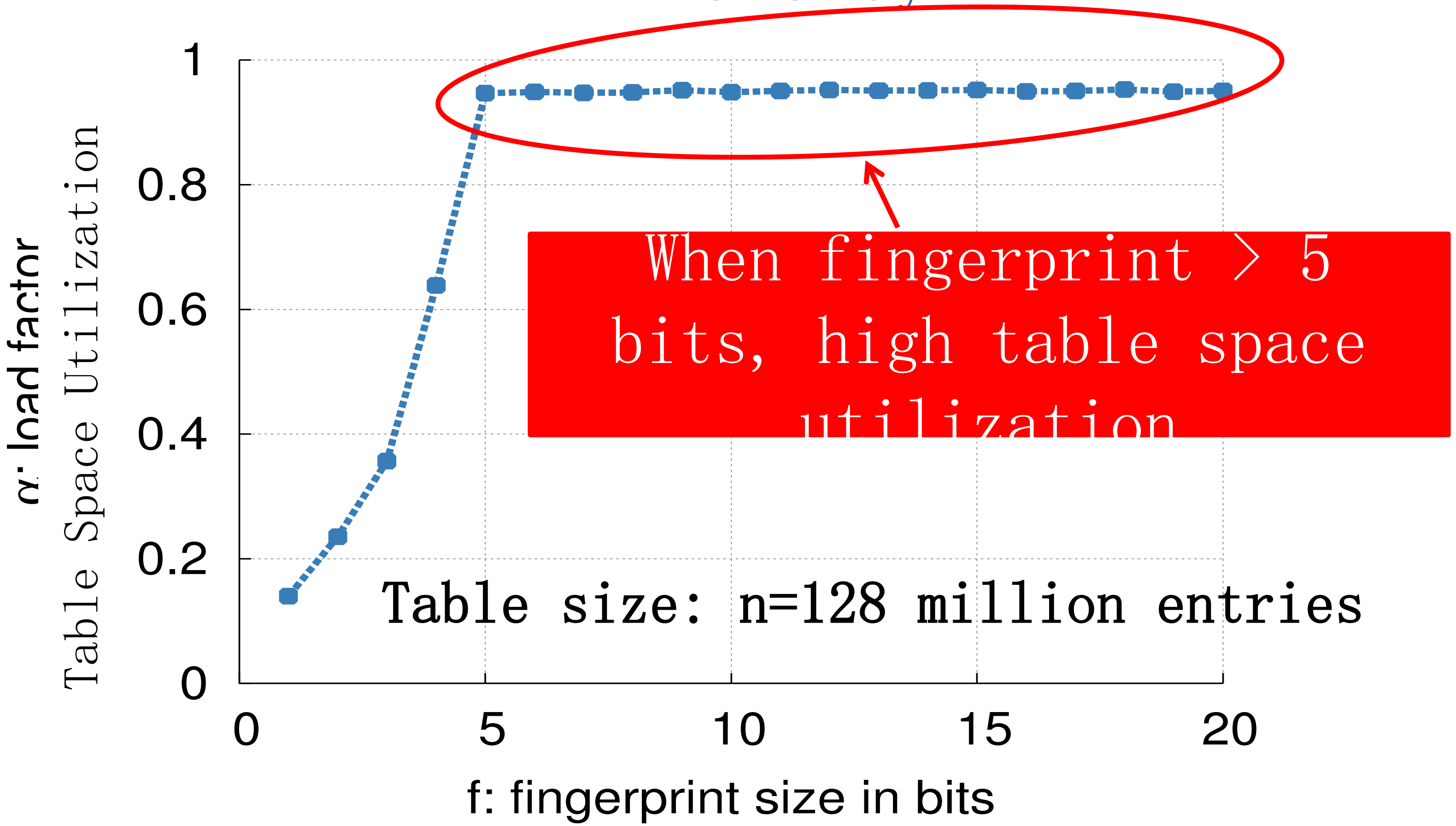
Partial Key Cuckoo Hashing

- Perform cuckoo hashing on fingerprints



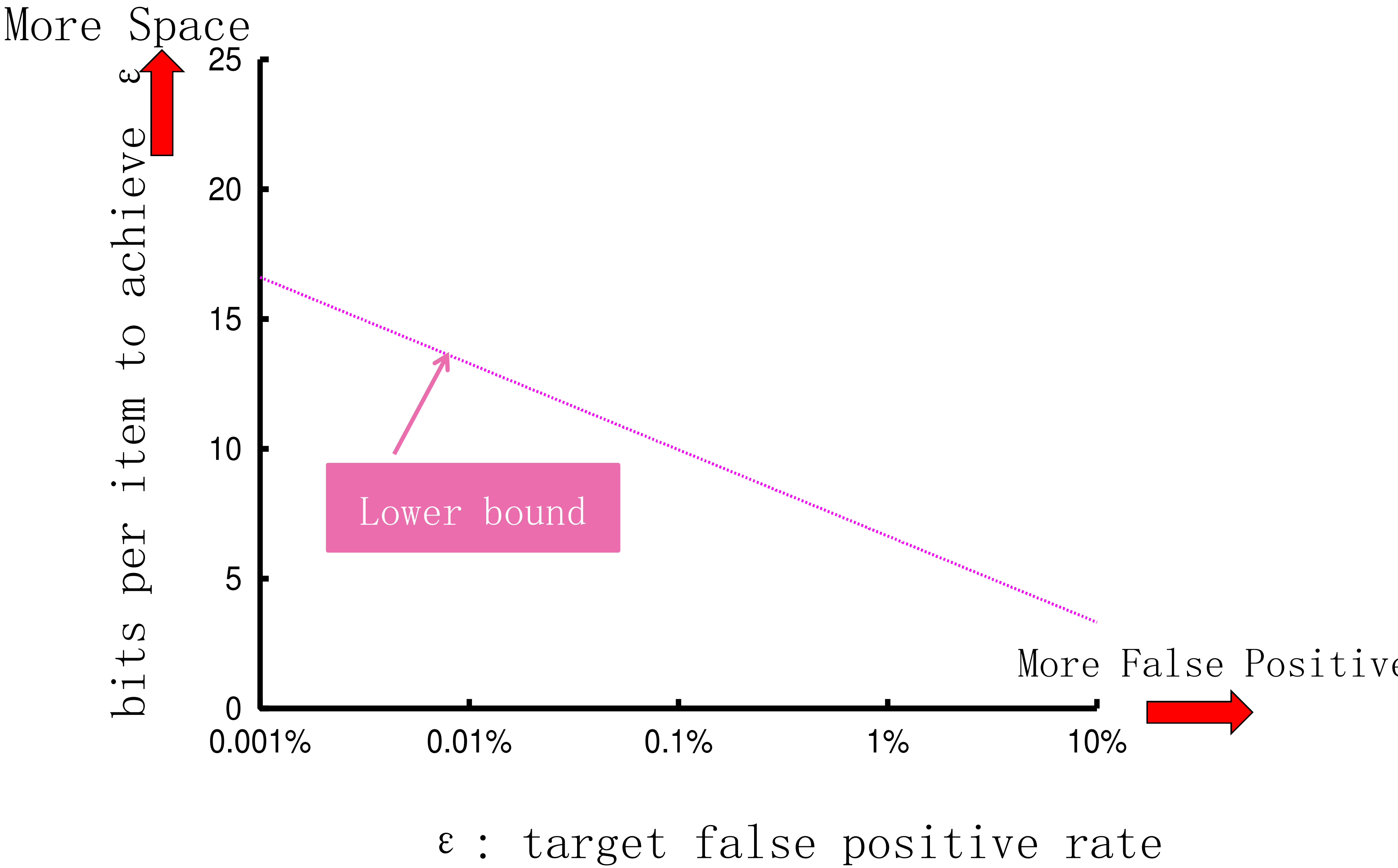
Can we still achieve high space utilization with partial-key cuckoo

Fingerprints Must Be "Long" for Space Efficiency

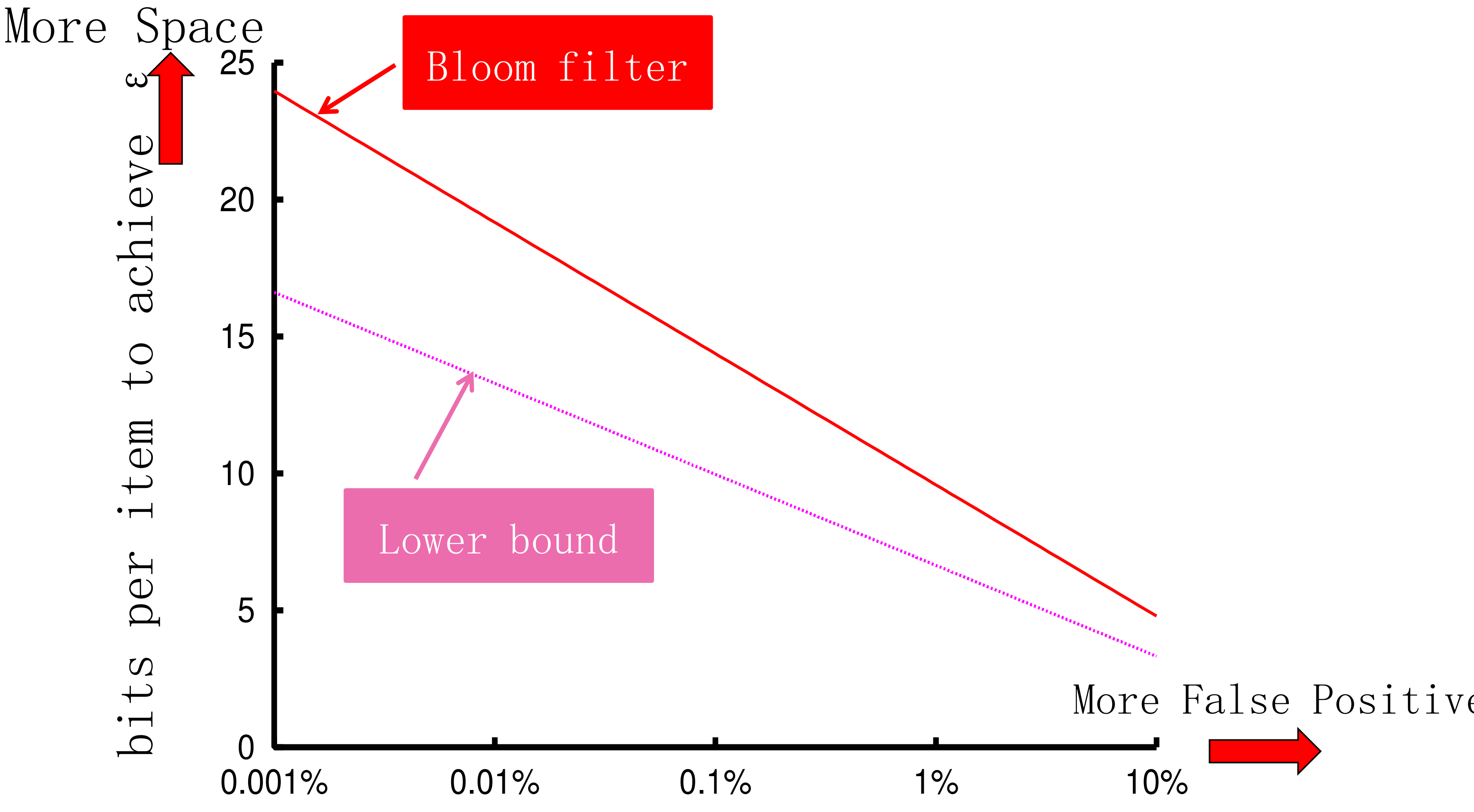


- Fingerprint must be Ω(logn/b) bits in theory
  - n: hash table size, b: bucket size
  - see more analysis in paper

Space Efficiency

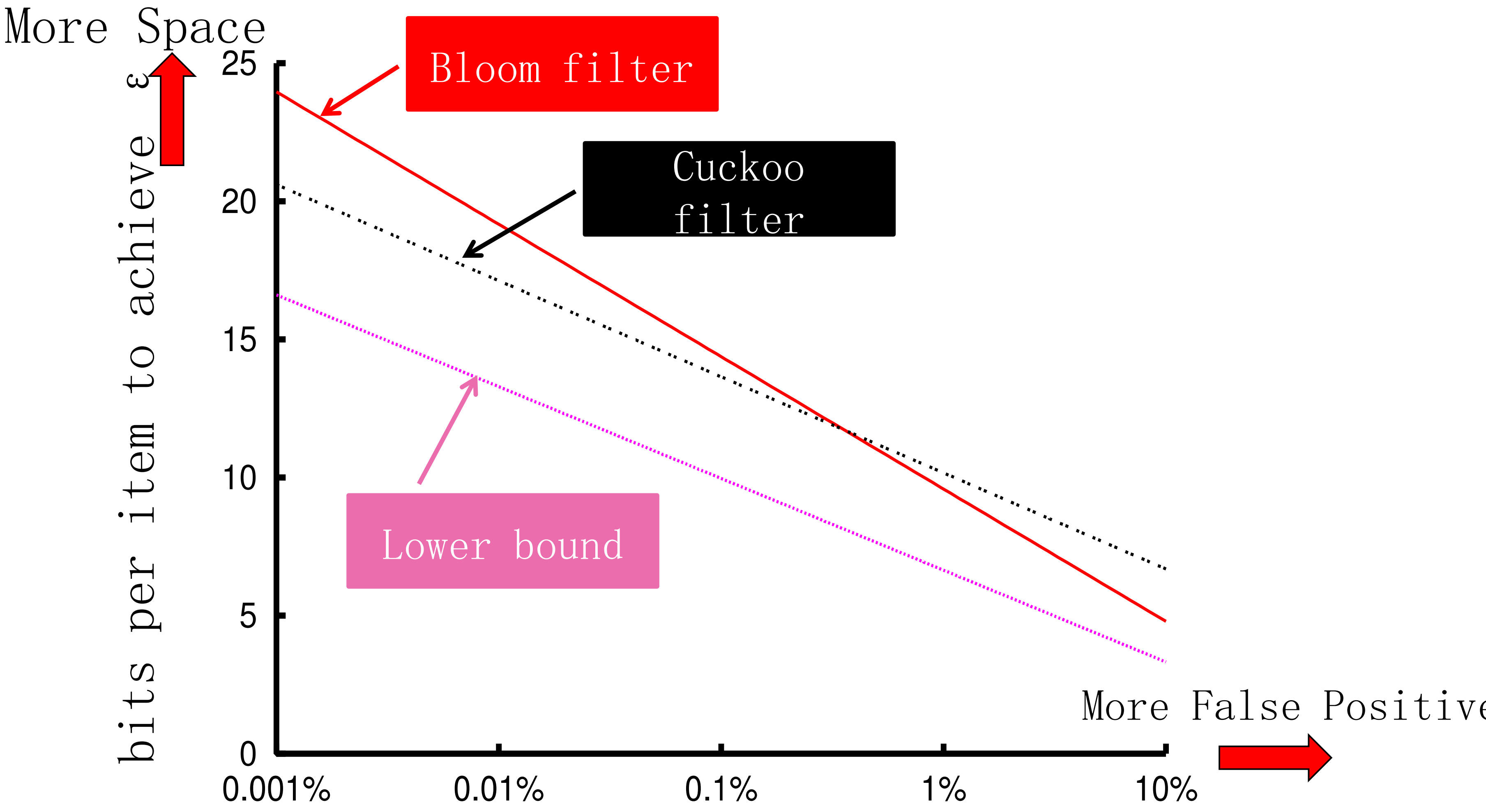


Space Efficiency



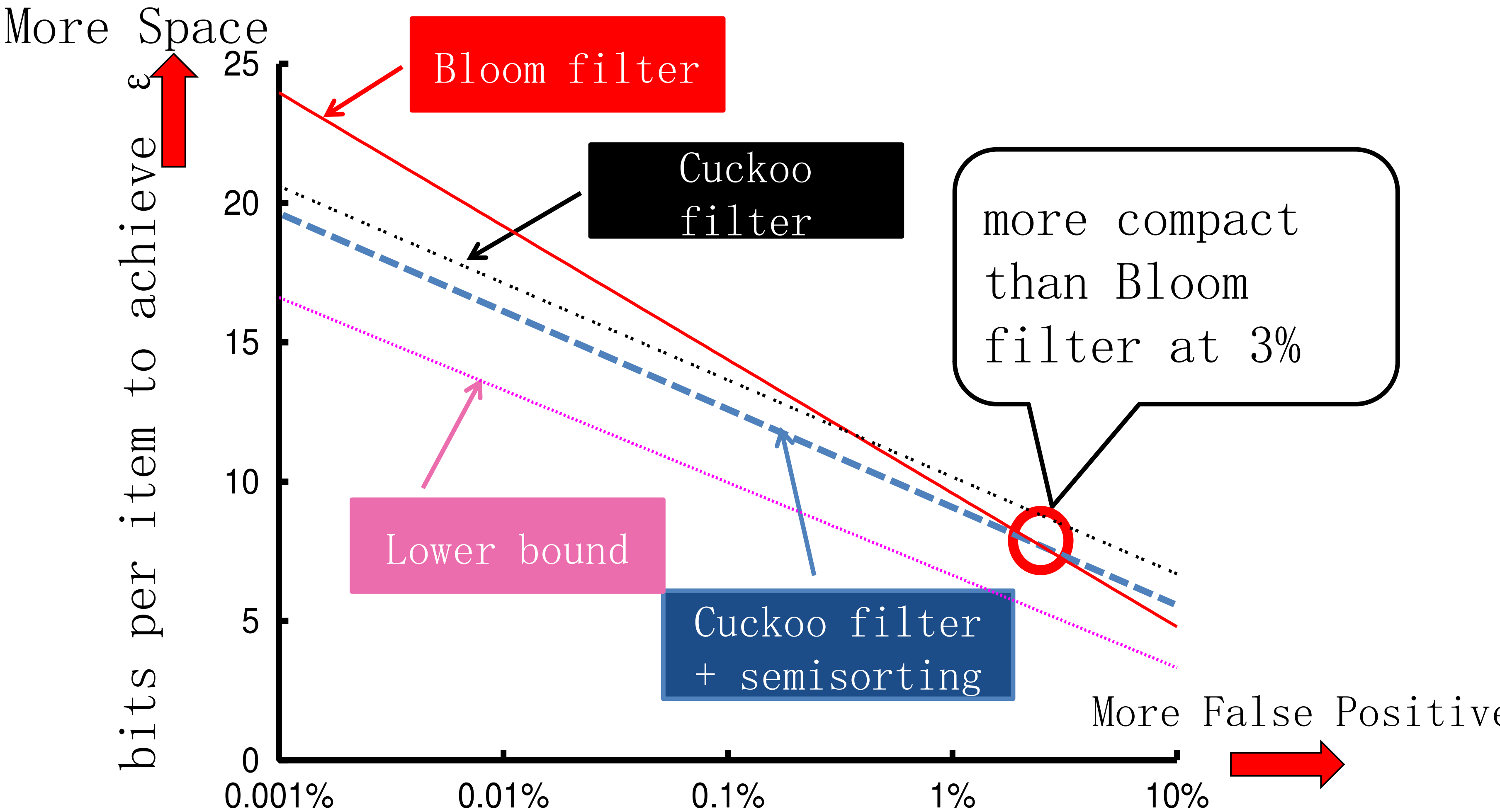
ε : target false positive rate

Space Efficiency



ε : target false positive rate

Space Efficiency



ε : target false positive rate

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Evaluation

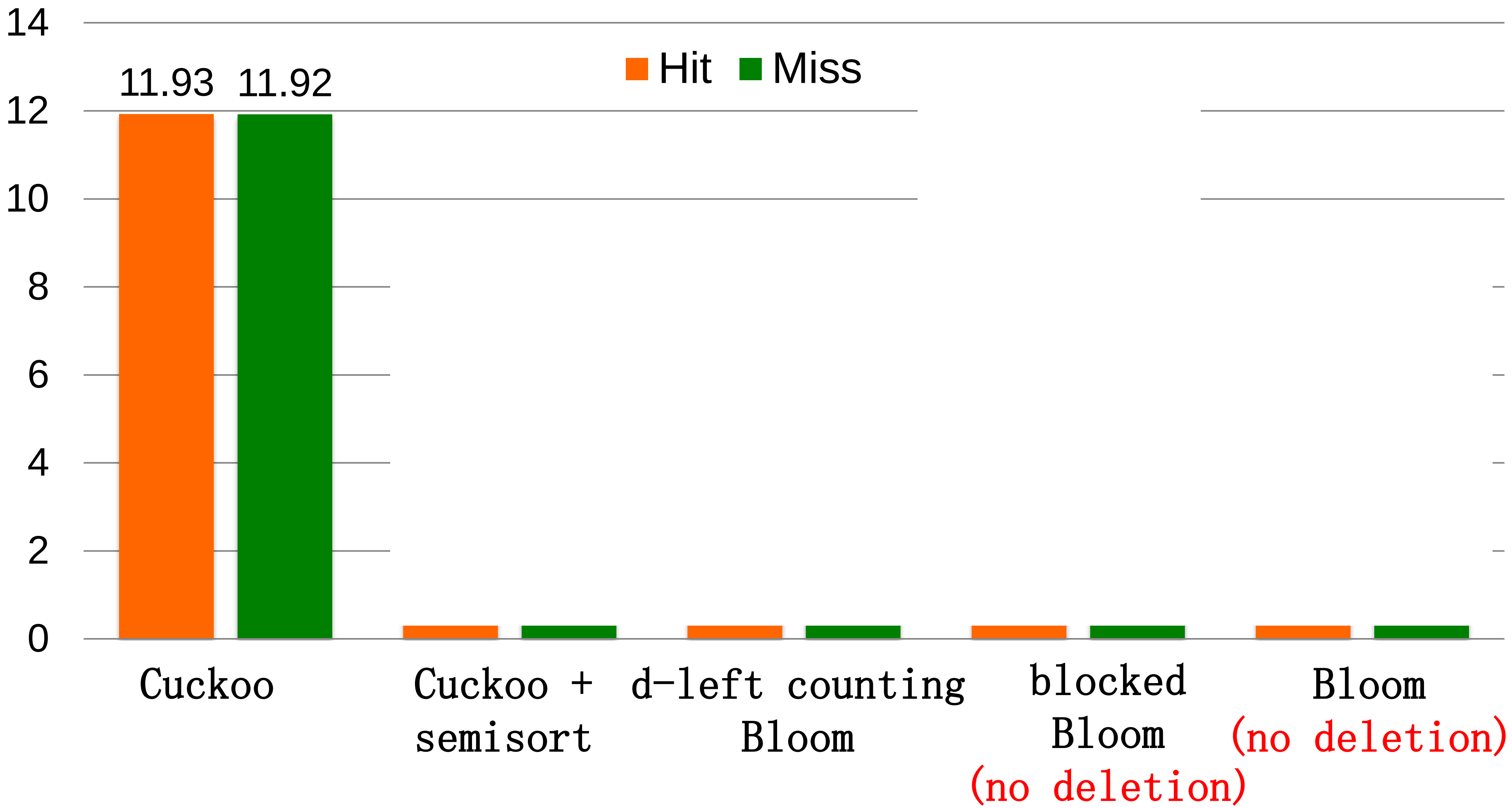
- Compare cuckoo filter with
  - Bloom filter (cannot delete)
  - Blocked Bloom filter [Putze2007] (cannot delete)
  - d-left counting Bloom filter [Bonomi2006]
  - Cuckoo filter + semisorting
  - More in the paper

- C++ implementation, single threaded

[Putze2007] Cache-, hash- and space- efficient bloom filters.

[Bonomi2006] Beyond Bloom filters: From approximate membership checks to approximate state machines.

Lookup Performance (MOPS)



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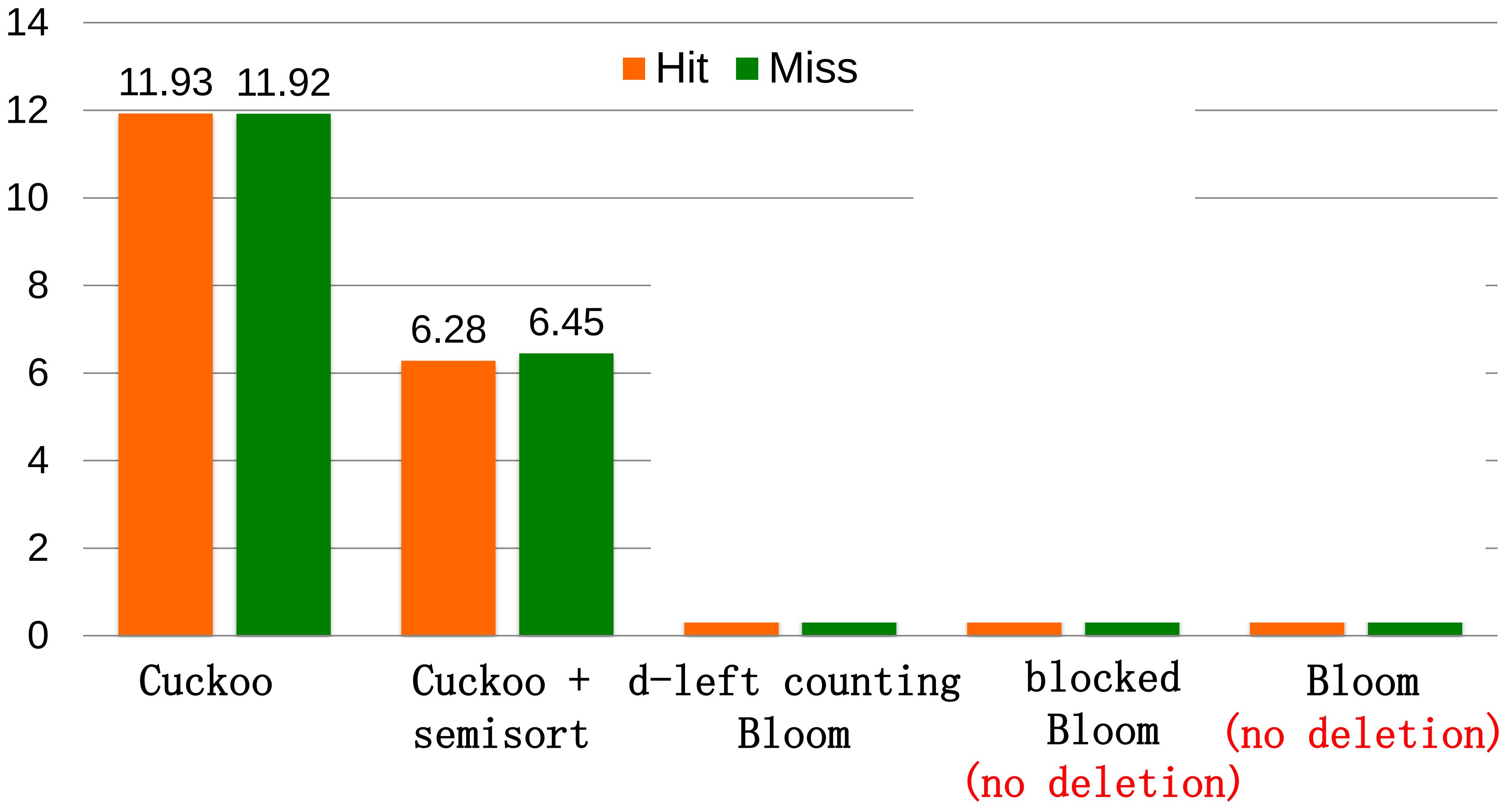

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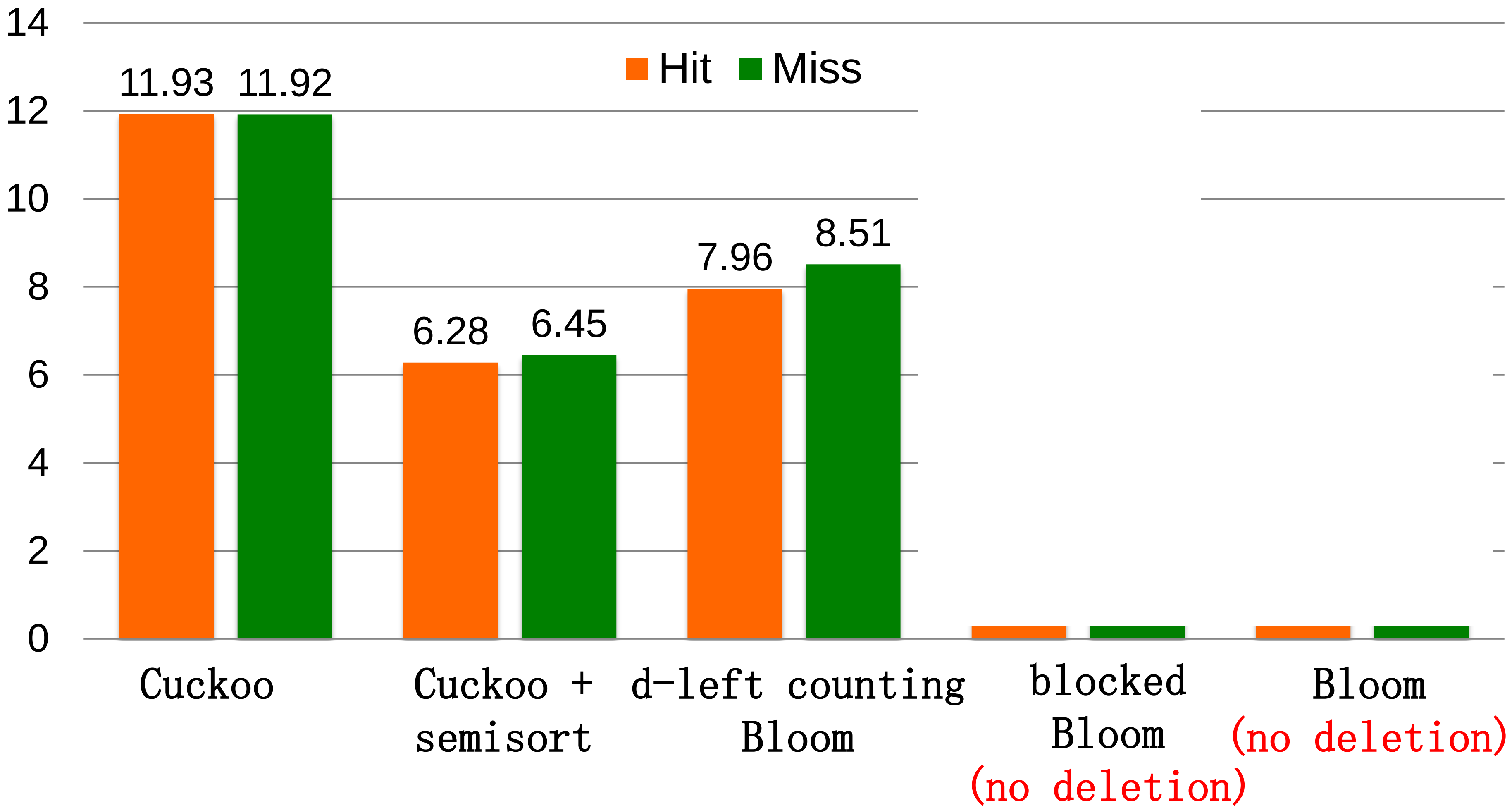

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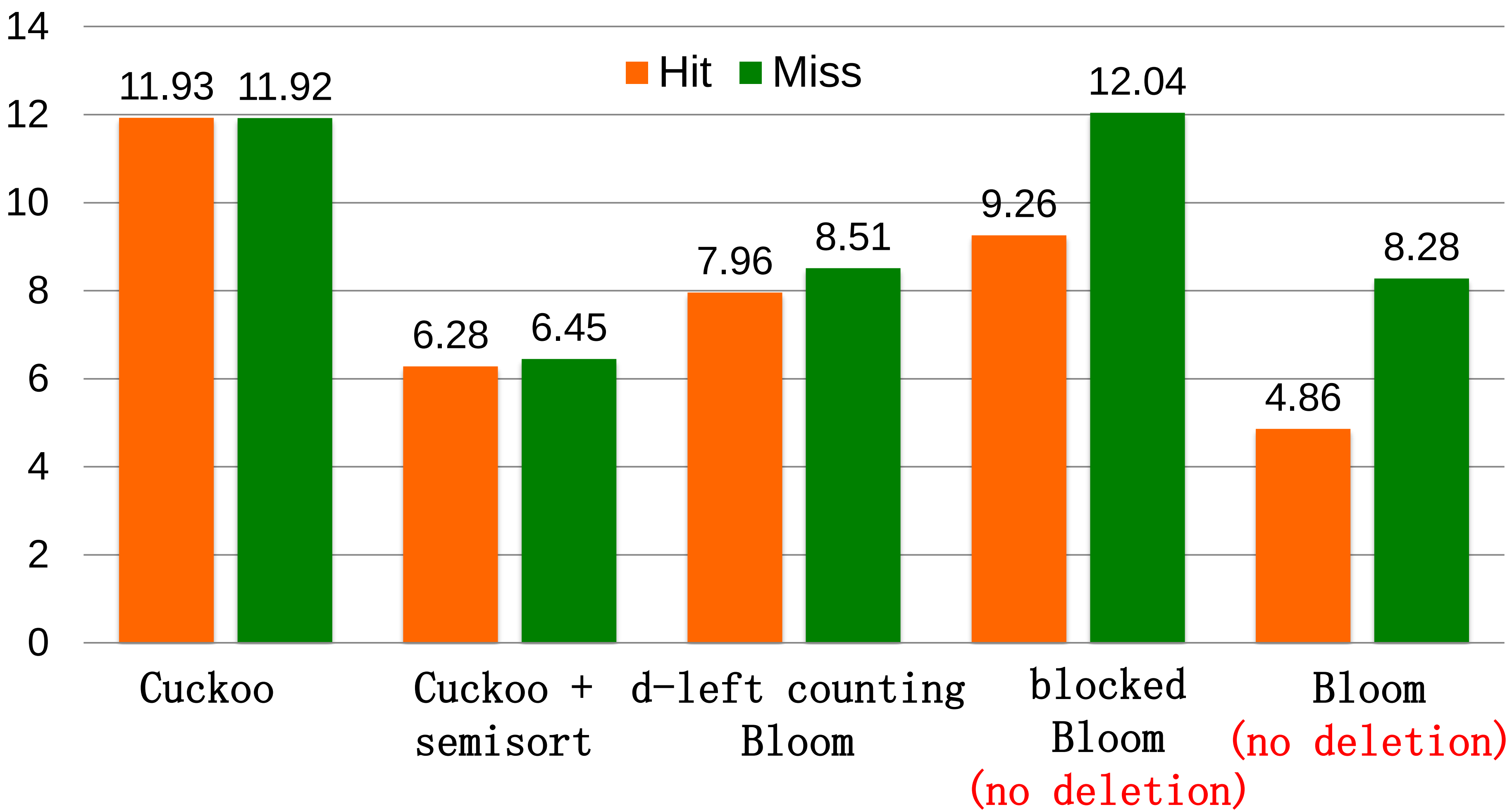
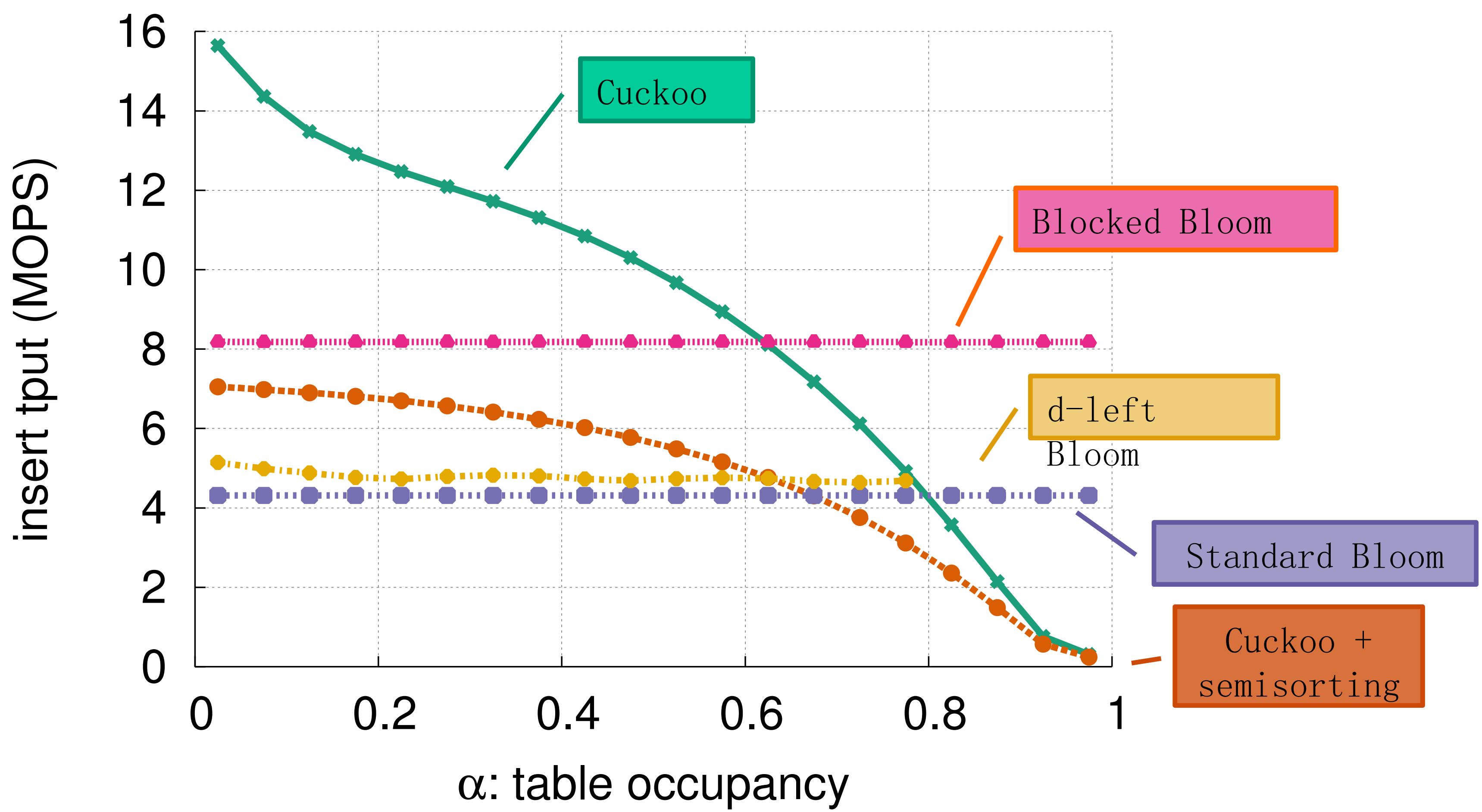


Cuckoo filter is among the fastest regardless

Insert Performance (MOPS)



Cuckoo filter has decreasing insert rate, but overall is only slower than blocked Bloom

Summary

- Cuckoo filter, a Bloom filter replacement:
  - Deletion support
  - High performance
  - Less Space than Bloom filters in practice
  - Easy to implement

- Source code available in C++:
  - https://github.com/efficient/cuckoofilter

Othello Hashing and Its Applications for Network Processing

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- Publications in *ICNP*'17, *SIGMETRICS*'17, *MECOMM*'17 and *Bioinformatics*

UNIVERSITY OF CALIFORNIA SANTA CRUZ

Background

- PhD in 2013 from UT Austin
  - with Simon Lam

- Research:
  - Computer networking
  - SDN/NFV
  - Internet of things
  - Security

Motivation

- Network algorithms always prefer small memory and fast processing speed.
  - Fast memory is precious resource on network devices
  - Needs to reach the line rate to avoid being a bottleneck, under large traffic volume
- More important in networks with layer-two semantics

Othello Hashing

- Essentially a key-value lookup structure
- Keys can be any names, addresses, identifiers, etc.
- Values should not be too long. At most 64 bit.

- For example
  - Key: network address; Value: link to forward a packet
  - Key: virtual IP; Value: direct IP

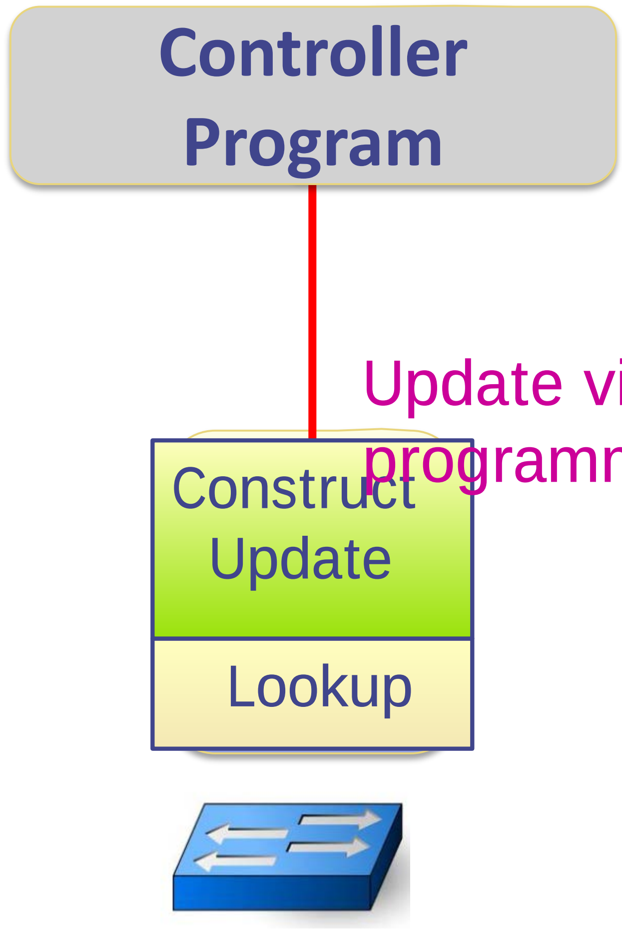
Why Othello is special

- Minimal query time: only two memory read operations (cachelines) per query.
- Minimal memory cost: 10%-30% of existing hash tables (e.g., Cuckoo).

Theoretical basis: **Minimal Perfect Hashing**

- Support dynamic updates: can be updated over a million times per second.

Idea of dynamic Othello lookups



Update via existing API of programmable networks

Optimize memory and query cost

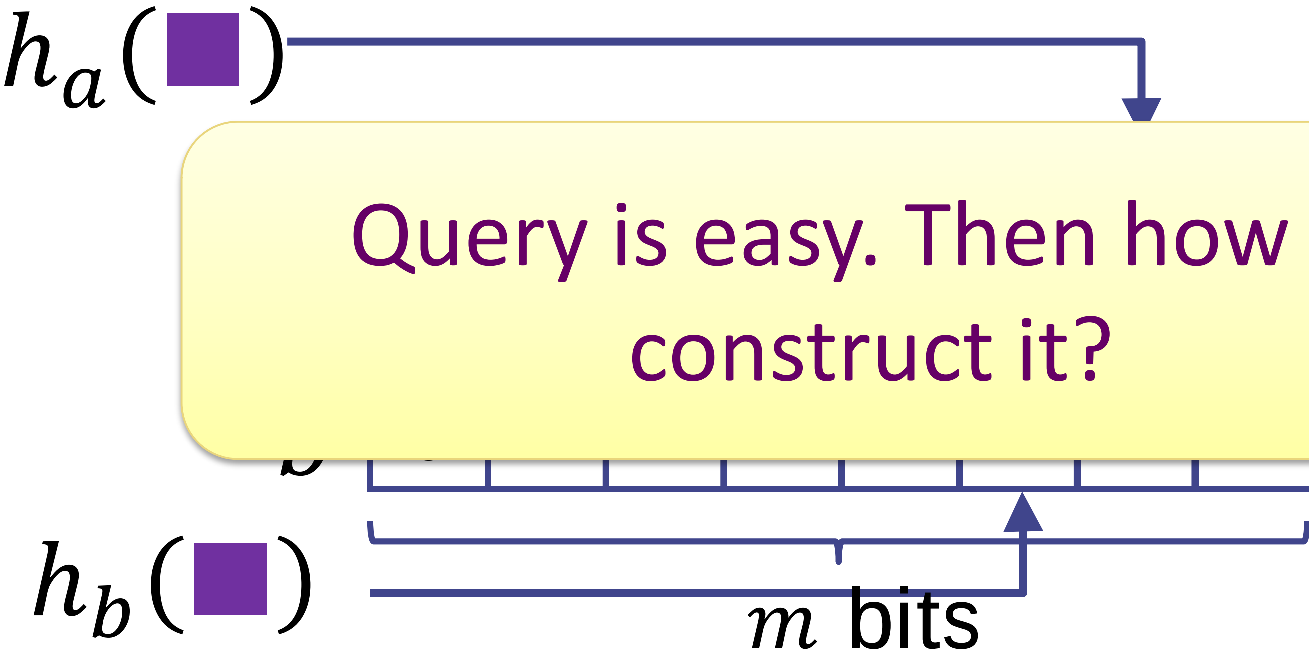
How Othello works

- **Basic version:** Classifies keys to **two sets** X and Y
  - Equivalent to key lookups for a 1-bit value
- Query result
  - $\tau(k) = 0 \Leftrightarrow k \in X$
  - $\tau(k) = 1 \Leftrightarrow k \in Y$
- **Advance version:** Classifies keys to 2^l sets
  - Equivalent to key lookups for a l-bit value

Othello Query Structure

n is # of keys

- Two bitmaps a, b with size m (m in $(1.33n, 2n)$)

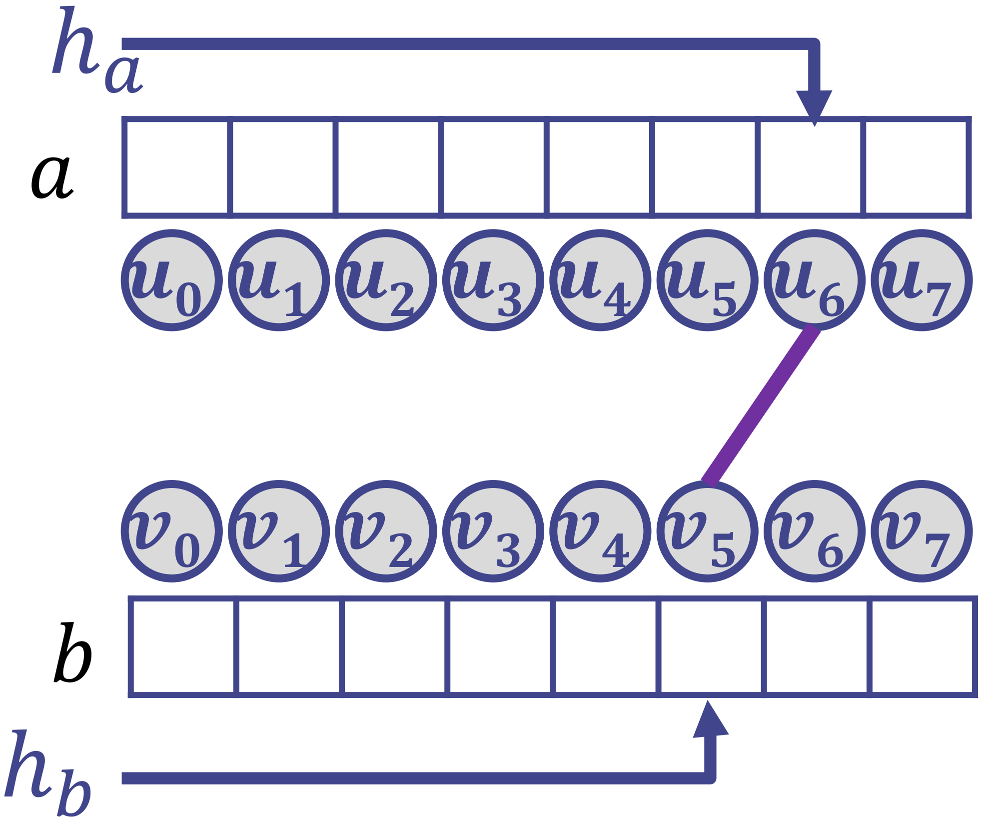


Query is easy. Then how to construct it?

■ is in set Y

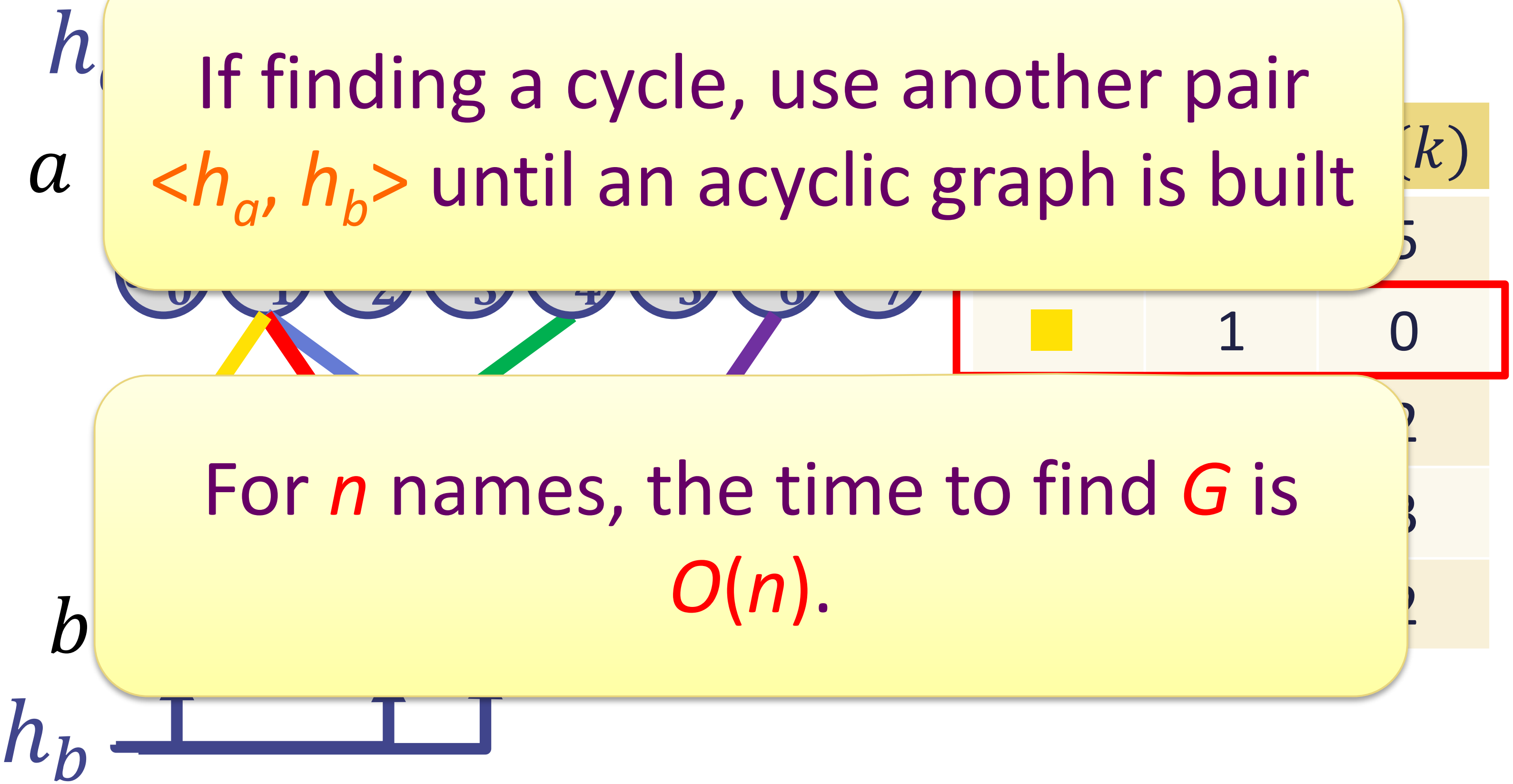
Othello Control Structure: Construct

- G: acyclic bipartite graph



k	$h_a(k)$	$h_b(k)$
■	6	5

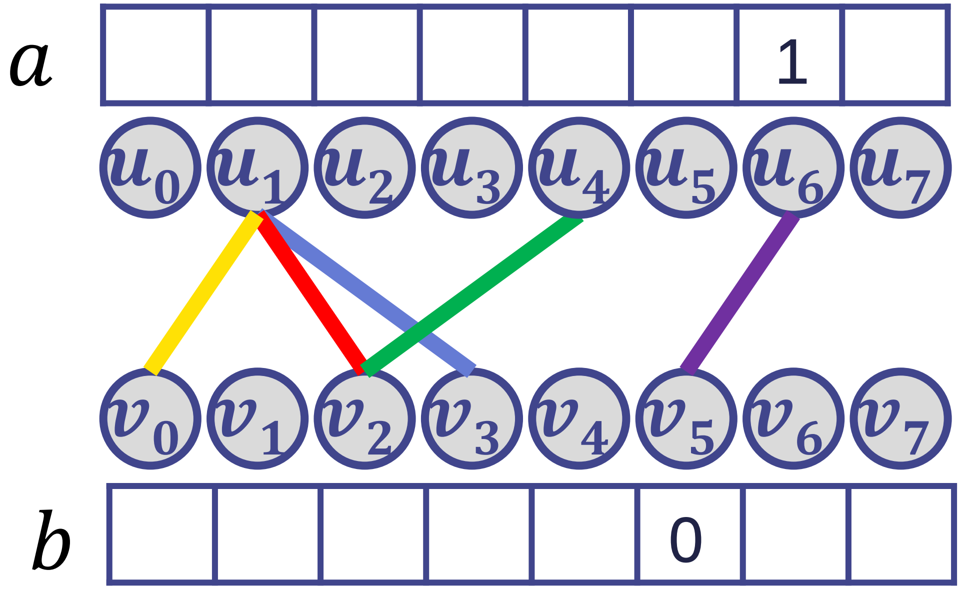
Othello Construct



If finding a cycle, use another pair $\langle h_a, h_b \rangle$ until an acyclic graph is built

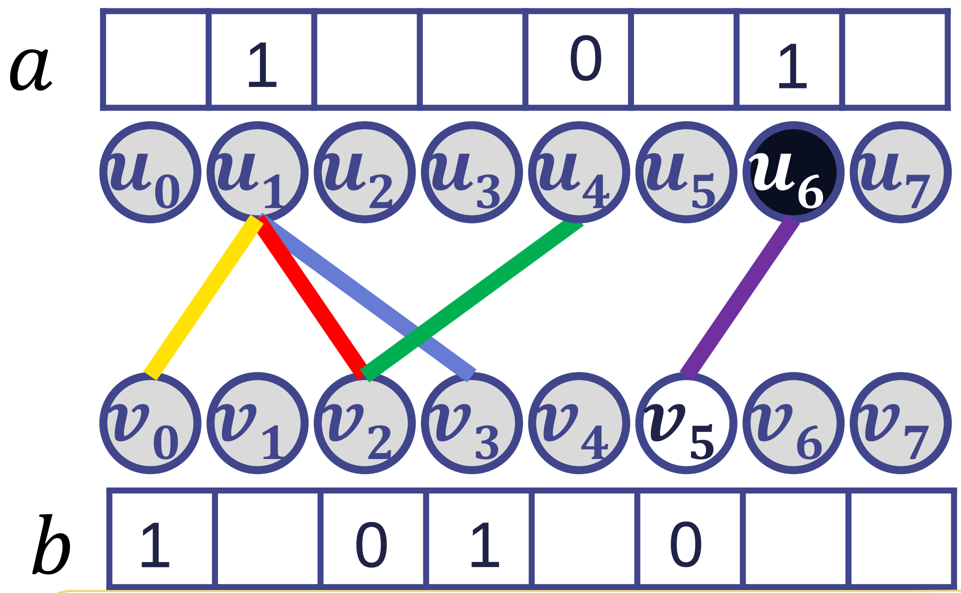
For n names, the time to find G is $O(n)$.

Compute Bitmap



k	$h_a(k)$	$h_b(k)$	set
■ (purple)	6	5	Y
■ (yellow)	1	0	
■ (red)	1	2	
■ (blue)	1	3	
■ (green)	4	2	

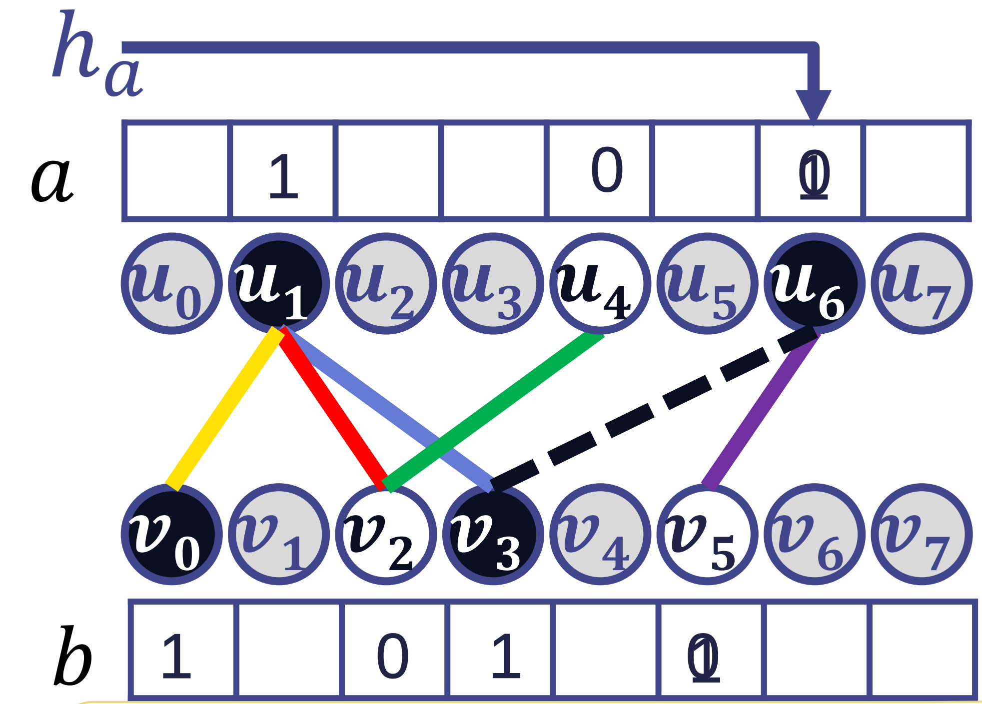
Compute Bitmap



k	$h_a(k)$	$h_b(k)$	set
(purple)	6	5	Y
(yellow)	1	0	X
(red)	1	2	Y
(blue)	1	3	X
(green)	4	2	X

If *G* is acyclic, easy to find a coloring plan

Name Addition – color flip

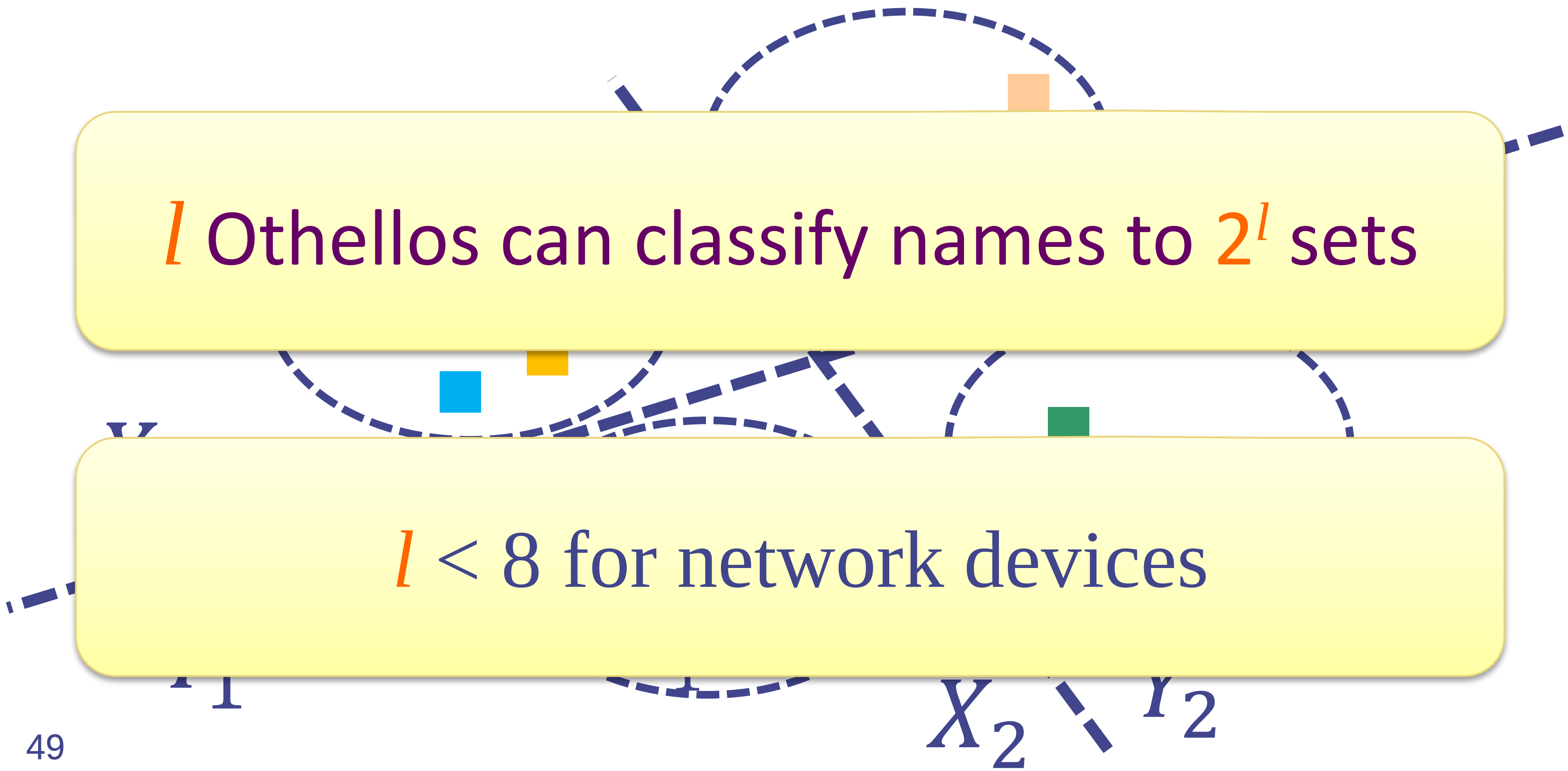


k	$h_a(k)$	$h_b(k)$	set
	6	5	Y
	1	0	X
	1	2	Y
	1	3	X
	4	2	X
	6	3	Y

If *G* is acyclic, flipping is trivial

L-Othello functionality

- Classifies names into 2^l sets: $Z_0, Z_1, \cdots, Z_{2^l-1}$

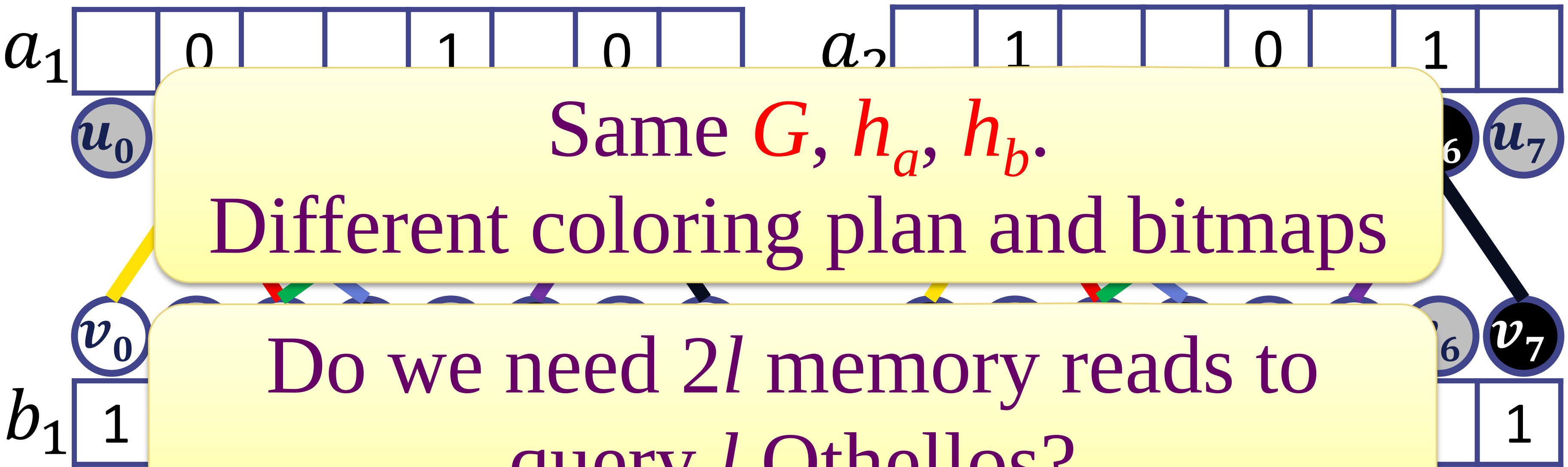


l Othellos can classify names to 2^l sets

$l < 8$ for network devices

Example

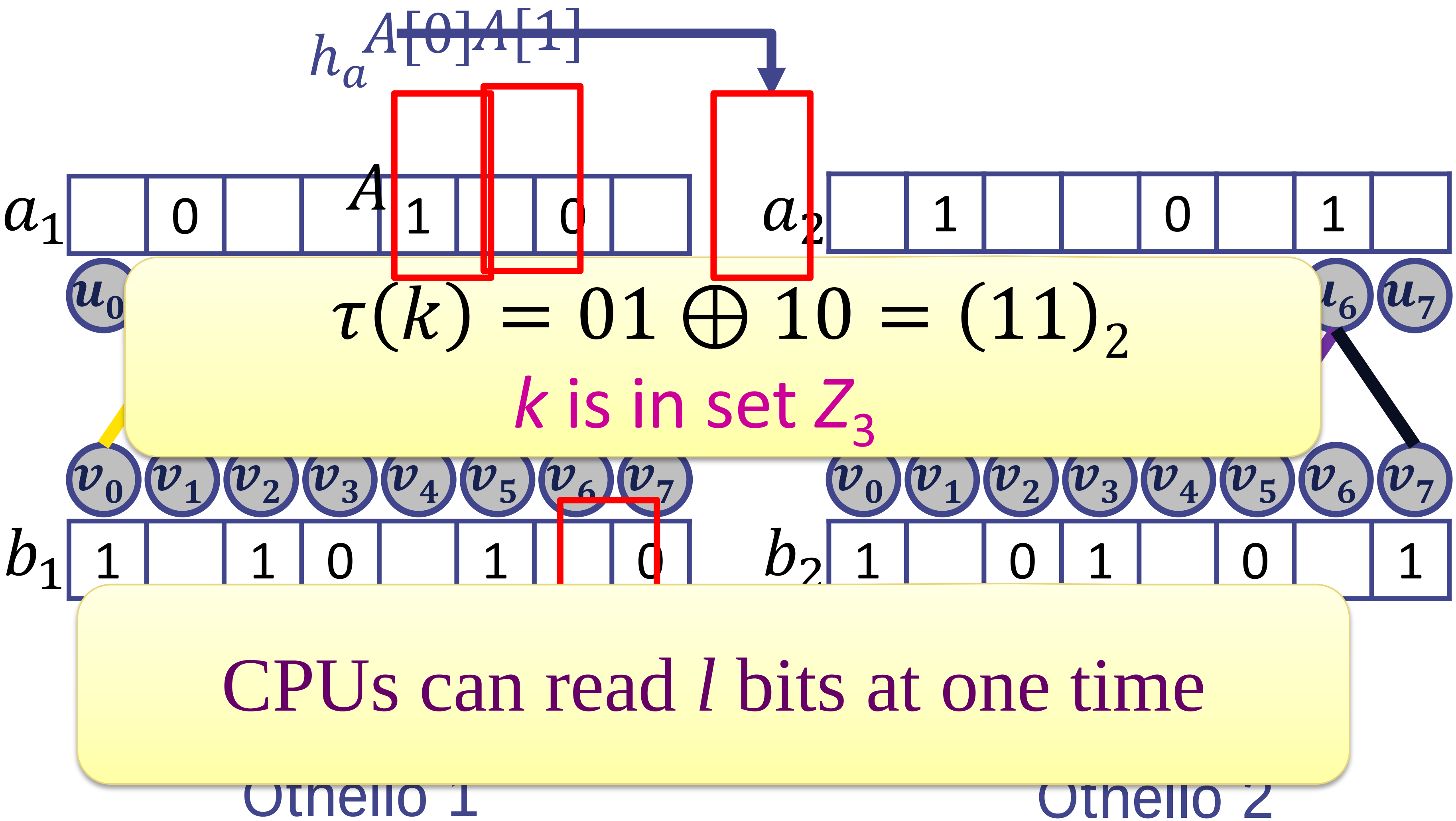
- Classify keys in 8 sets: $Z_0, Z_1, \cdots, Z_7$
- Orthogonal separation of sets
  - $X_3 = Z_0 \cup Z_1 \cup Z_2 \cup Z_3$; $Y_3 = Z_4 \cup Z_5 \cup Z_6 \cup Z_7$.
  - $X_2 = Z_0 \cup Z_1 \cup Z_4 \cup Z_5$; $Y_2 = Z_2 \cup Z_3 \cup Z_6 \cup Z_7$.
  - $X_1 = Z_0 \cup Z_2 \cup Z_4 \cup Z_6$; $Y_1 = Z_1 \cup Z_3 \cup Z_5 \cup Z_7$.
- **$6=(110)_2$** $k \in Y_3 \cap Y_2 \cap X_1 \Rightarrow k \in Z_6$
- l Othellos : classify keys in 2^l sets.



Same G, h_a, h_b.
Different coloring plan and bitmaps

Do we need $2l$ memory reads to query l Othellos?

Othello 1 Same $X \cup Y$ Othello 2



h_a
$A[0]$ $A[1]$
A
a_1
0
1
0
a_2
1
0
1
$\tau(k) = 01 \oplus 10 = (11)_2$
k is in set Z_3
v_0 v_1 v_2 v_3 v_4 v_5 v_6 v_7
v_0 v_1 v_2 v_3 v_4 v_5 v_6 v_7
b_1
1 1 0 1 0
b_2
1 0 1 0 1
CPUs can read *l* bits at one time
Othello 1
Othello 2

Alien keys

- What is $\tau(k) = a[h_a(k)] \oplus b[h_b(k)]$ when k is not in S?
  - An arbitrary value

- $\tau(k)$ return 1 with when
  - $a[i] = 1$ && $b[j] = 0$, or
  - $a[i] = 0$&& $b[j] = 1$

Applications of Othello

- 1. Forwarding Information Base (FIB)
- 2. Software load balancer
- 3. Data placement and lookup
- 4. Private queries
- 5. Genomic sequencing search
- And more…

A Concise FIB

- Resolving FIB explosion is crucial
  - For layer-two interconnected data centers
  - For OpenFlow-like fine-grained flow control
- Concise using *l*-Othello is a portable solution
  - In hardware devices
  - Or software switches

A Fast, Small, and Dynamic Forwarding Information Base, In ACM SIGMETRICS 2017
A Concise Forwarding Information Base for Scalable and Fast Name Switching, in IEEE ICNP 2017.

Network-wide updating

- If all devices share a same set of network names/addresses
  - Such as in layer-two Ethernet-based data centers
  - All Othellos will share a same *G*.
  - Hence network-wide updating is very efficient!
- Update consistency also provided

Implementation of three prototypes

- 1. Memory mode
  - Query and control structures running on different threads.
- 2. CLICK modular router
- 3. Intel Data Plane Development Kit (DPDK)

Comparison:

- Buffalo

Yu, Fabrikant, Rexford, in CoNEXT'09

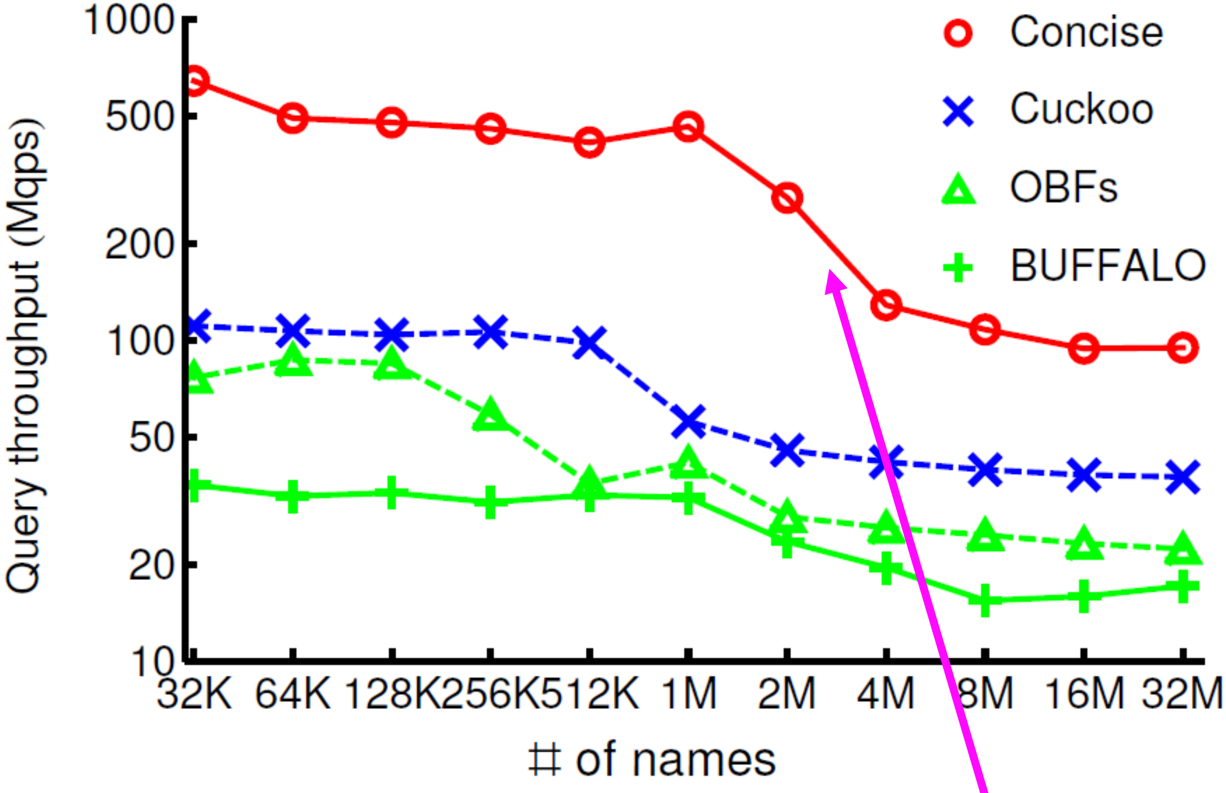
- Cuckoo hashing

Zhou, Fan, Lim, Kaminsky, Andersen,
in CoNEXT'13 and SIGCOMM'15

Comparison: Memory size

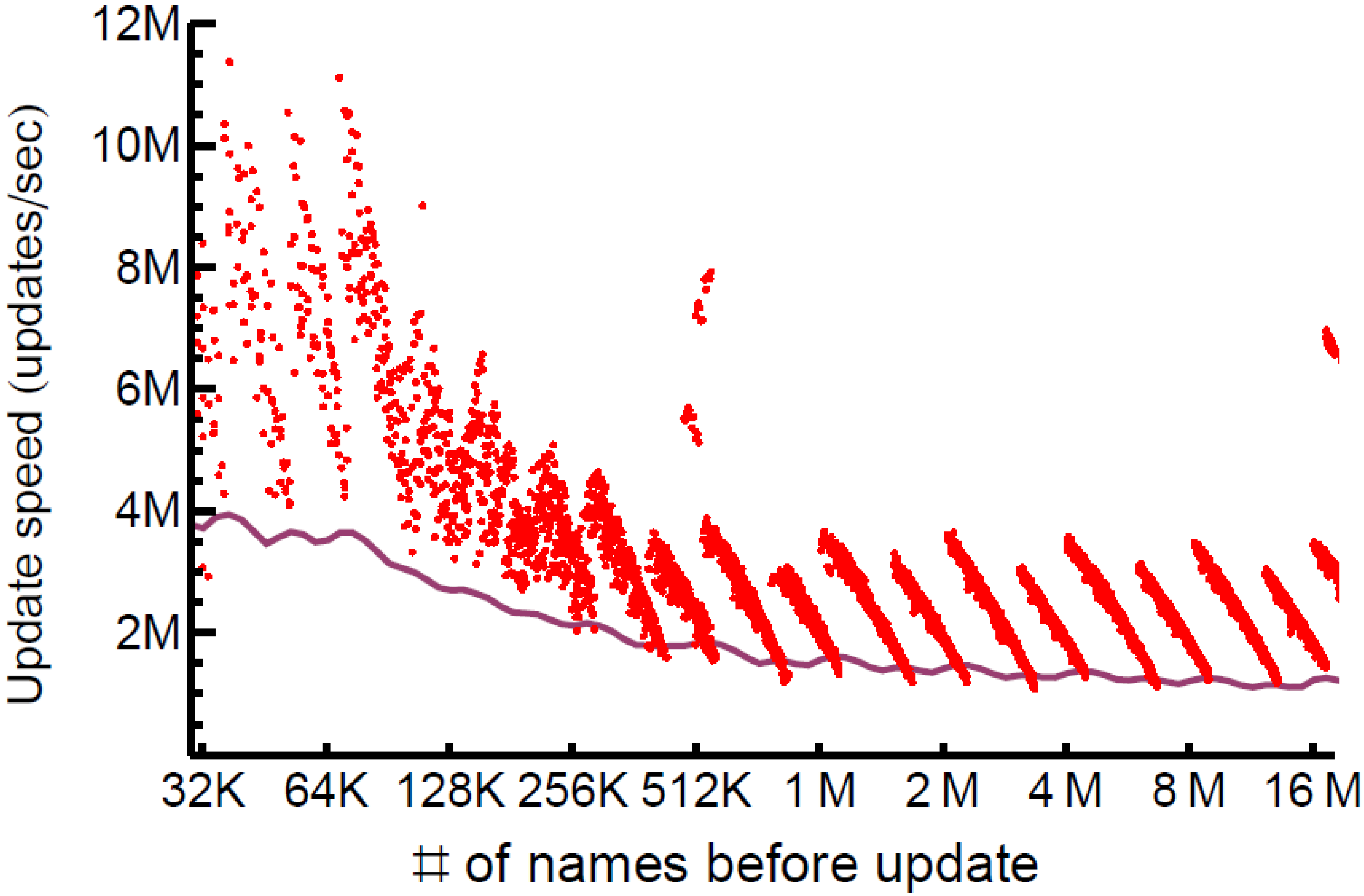
FIB Example			Memory Size		
Name Type	# Names	# Actions	Concise	Cuckoo	Buffalo
MAC (48 bits)	$7*10^5$	16	1M	5.62M	2.64M
MAC (48 bits)	$5*10^6$	256	16M	40.15M	27.70M
MAC (48 bits)	$3*10^7$	256	128M	321.23M	166.23M
IPv4 (32 bits)	$1*10^6$	16	2M	4.27M	3.77M
IPv6 (128 bits)	$2*10^6$	256	8M	34.13M	11.08M
OpenFlow (356 bits)	$3*10^5$	256	1M	14.46M	1.67M
OpenFlow (356 bits)	$1.4*10^6$	65536	8M	67.46M	18.21M
File name (varied)	359194	16	512K	19.32M	1.35M

Query speed



2x to 4x speed advantage

Update speed



For unknown network names

- 1. For data centers with most internal traffic
  - Such situation is rare
- 2. For networks with much incoming traffic
  - A filter can be installed at a firewall
- 3. Concise may include an *r*-bit checksum.
  - A lookup still requires 2 memory accesses in total, as long as $l + r <= 64$.

Thank You

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https://users.soe.ucsc.edu/~qian/