Cheap and Large CAMs for High Performance Data-Intensive Networked Systems

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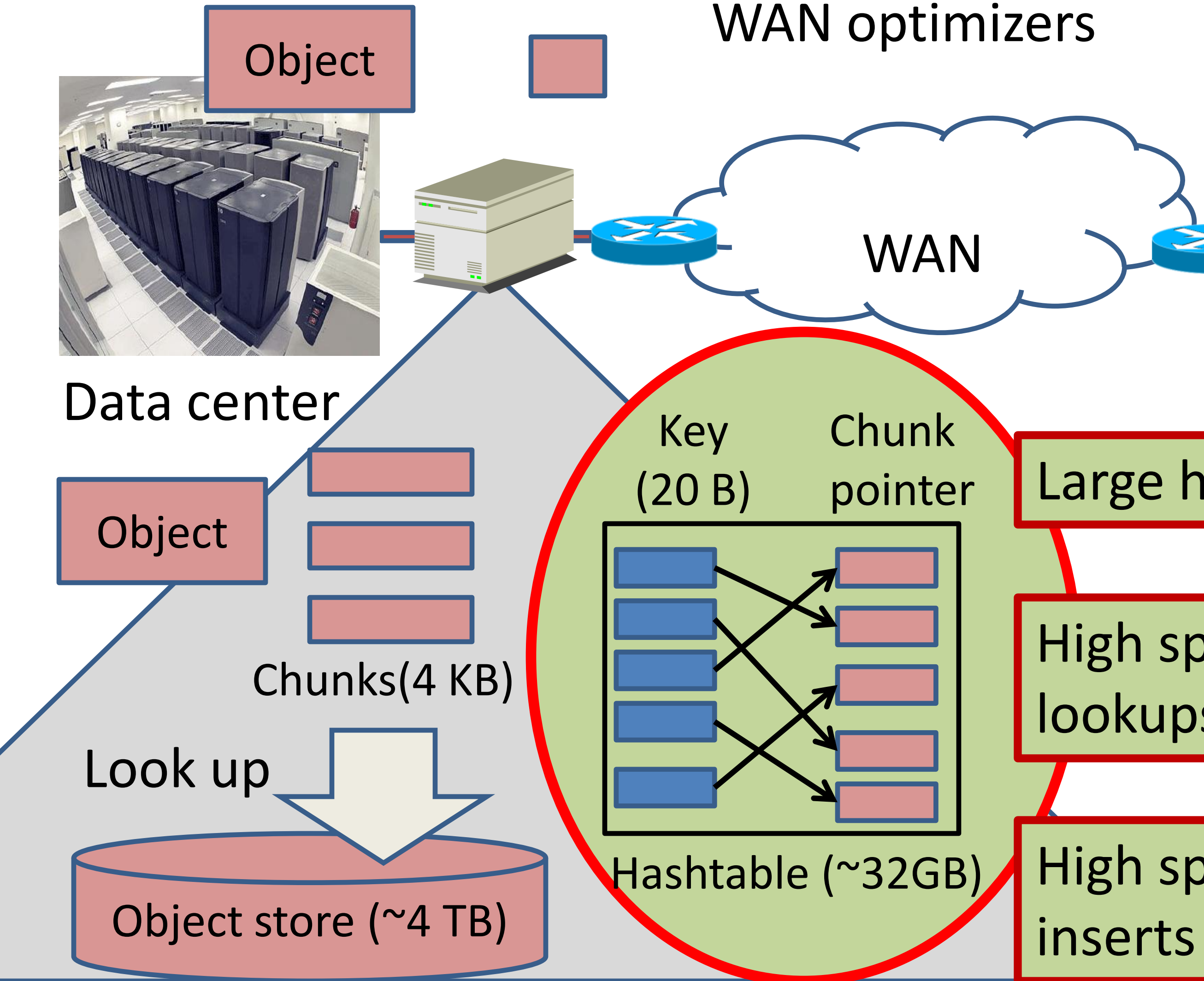
New data-intensive networked systems

Large hash tables (10s to 100s of GBs)

New data-intensive networked systems



Large hash tables (32 GB)

High speed (~10K/sec) lookups for 500 Mbps link

High speed (~10 K/sec) inserts and evictions

New data-intensive networked systems

- Other systems
  - De-duplication in storage systems (e.g., Datadomain)
  - CCN cache (Jacobson et al., CONEXT 2009)
  - DONA directory lookup (Koponen et al., SIGCOMM 2006)

Cost-effective large hash tables

Cheap Large cAMs

Candidate options

Too slow

$^{+}$Price statistics from 2008-09

	Random reads/sec	Random writes/sec	Cost (128 GB)
Disk	250	250	$\$30^{+}$
DRAM	300K	300K	$\$120\text{K}^{+}$
Flash-SSD	10K*	5K*	$\$225^{+}$

* Derived from latencies on Intel M-18 SSD in experiments

Too expensive

2.5 ops/sec/$

Slow writes

How to deal with slow writes of Flash SSD

Our CLAM design

- New data structure “BufferHash” + Flash
- Key features
  - Avoid random writes, and perform sequential writes in a batch
    - Sequential writes are 2X faster than random writes (Intel SSD)
    - Batched writes reduce the number of writes going to Flash
  - Bloom filters for optimizing lookups

BufferHash performs orders of magnitude better than DRAM based traditional hash tables in ops/sec/$

Outline

- Background and motivation

- *CLAM design*
  - *Key operations (insert, lookup, update)*
  - Eviction
  - Latency analysis and performance tuning

- Evaluation

Flash/SSD primer

- Random writes are expensive

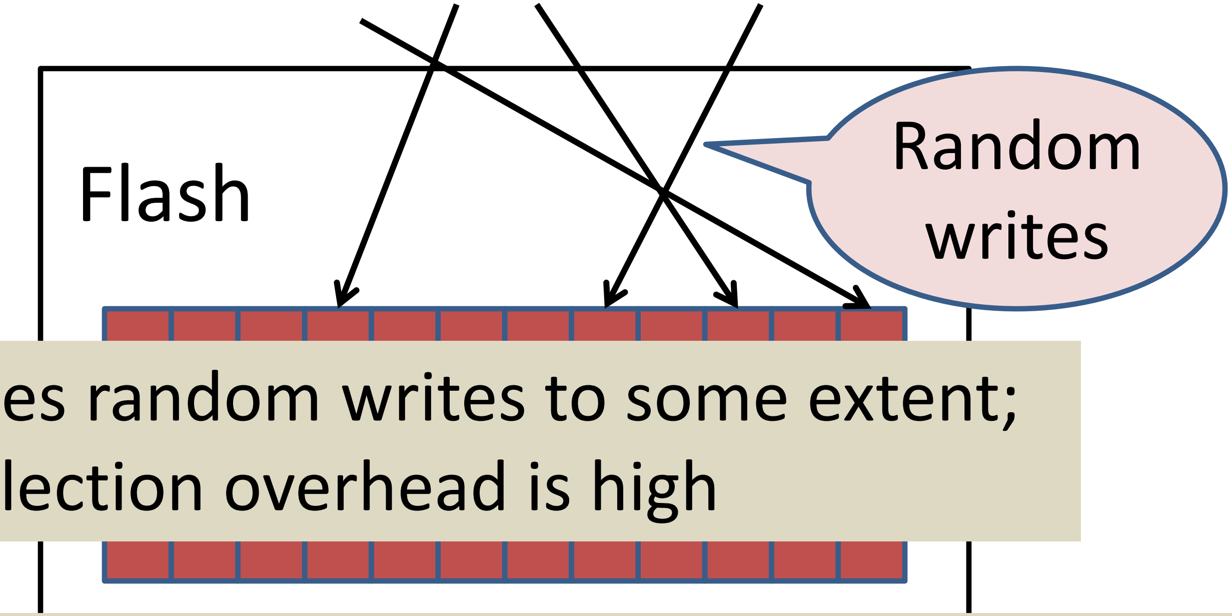
  Avoid random page writes

- Reads and writes happen at the granularity of a flash page

  I/O smaller than page should be avoided, if possible

Conventional hash table on Flash/SSD

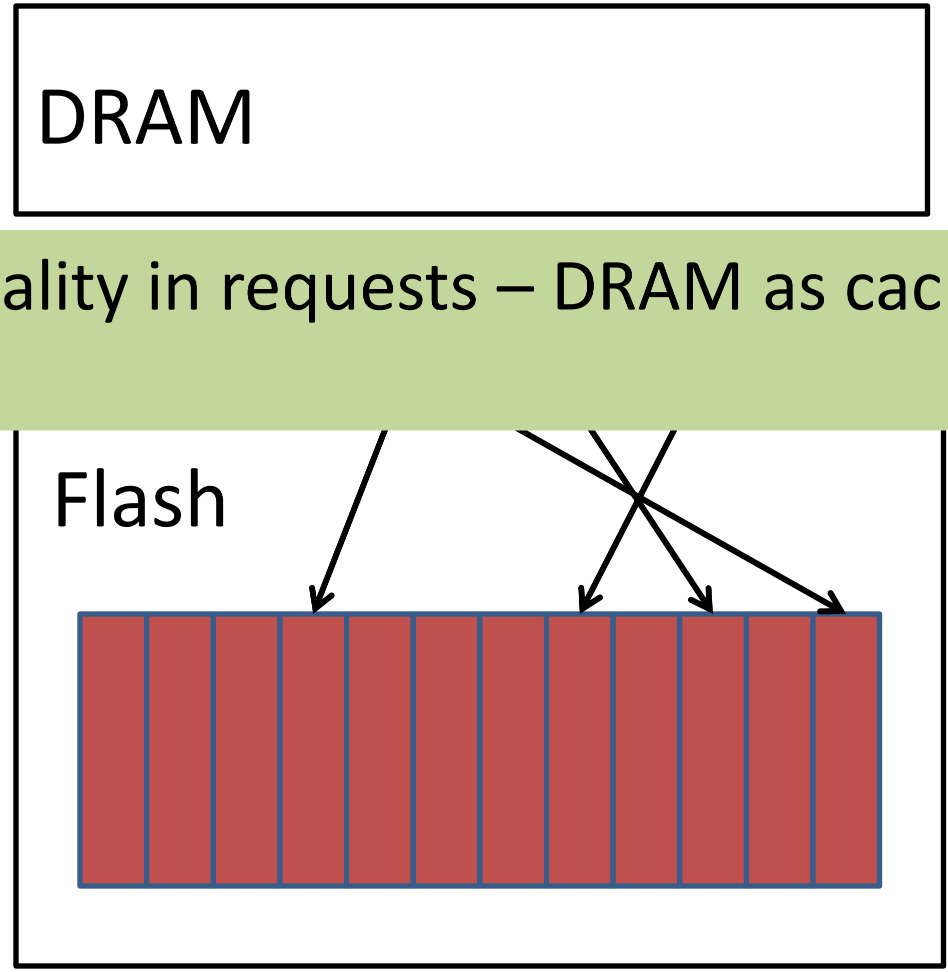
Keys are likely to hash to random locations



SSDs: FTL handles random writes to some extent;
But garbage collection overhead is high

~200 lookups/sec and ~200 inserts/sec with WAN optimizer workload, << 10 K/s and 5 K/s

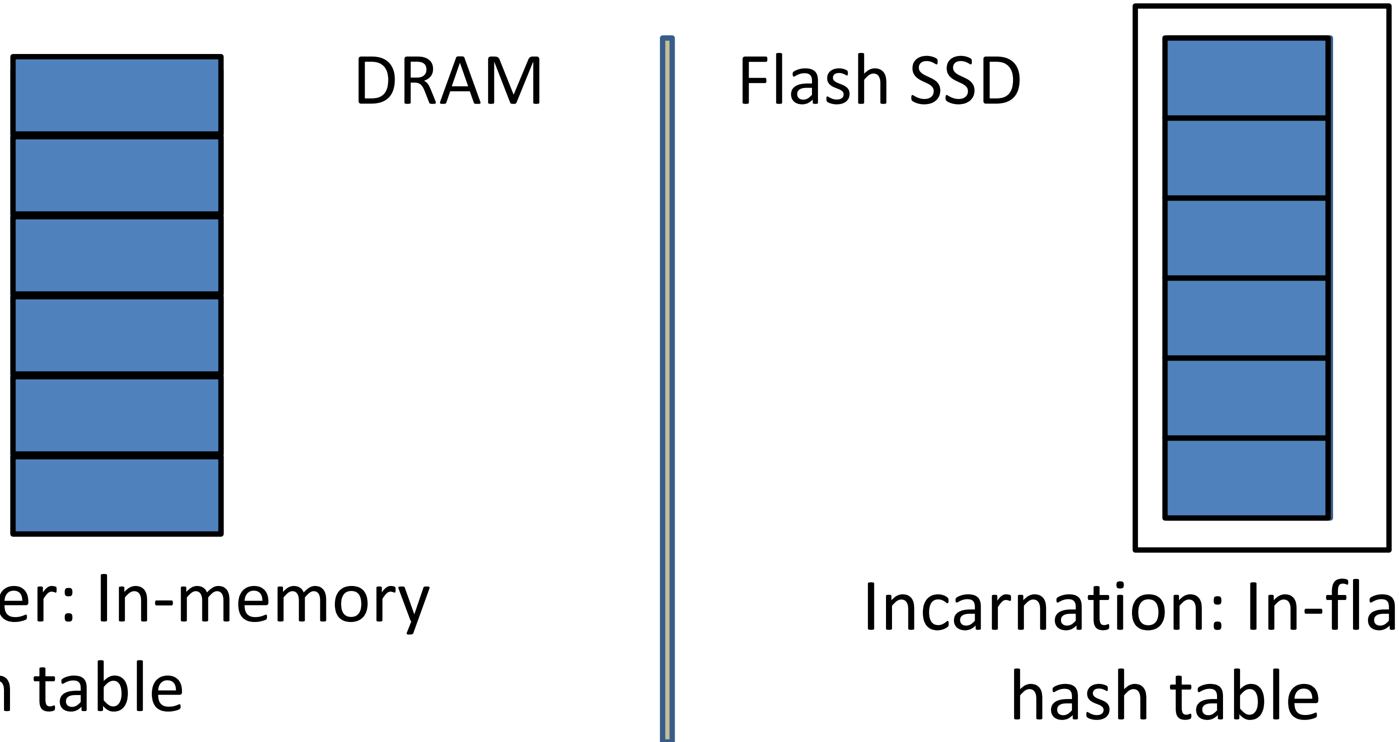
Conventional hash table on Flash/SSD



Can’t assume locality in requests – DRAM as cache won’t work

Our approach: Buffering insertions

- Control the impact of random writes
- Maintain small hash table (**buffer**) in memory
- As in-memory buffer gets full, write it to flash
  - We call in-flash buffer, **incarnation** of **buffer**



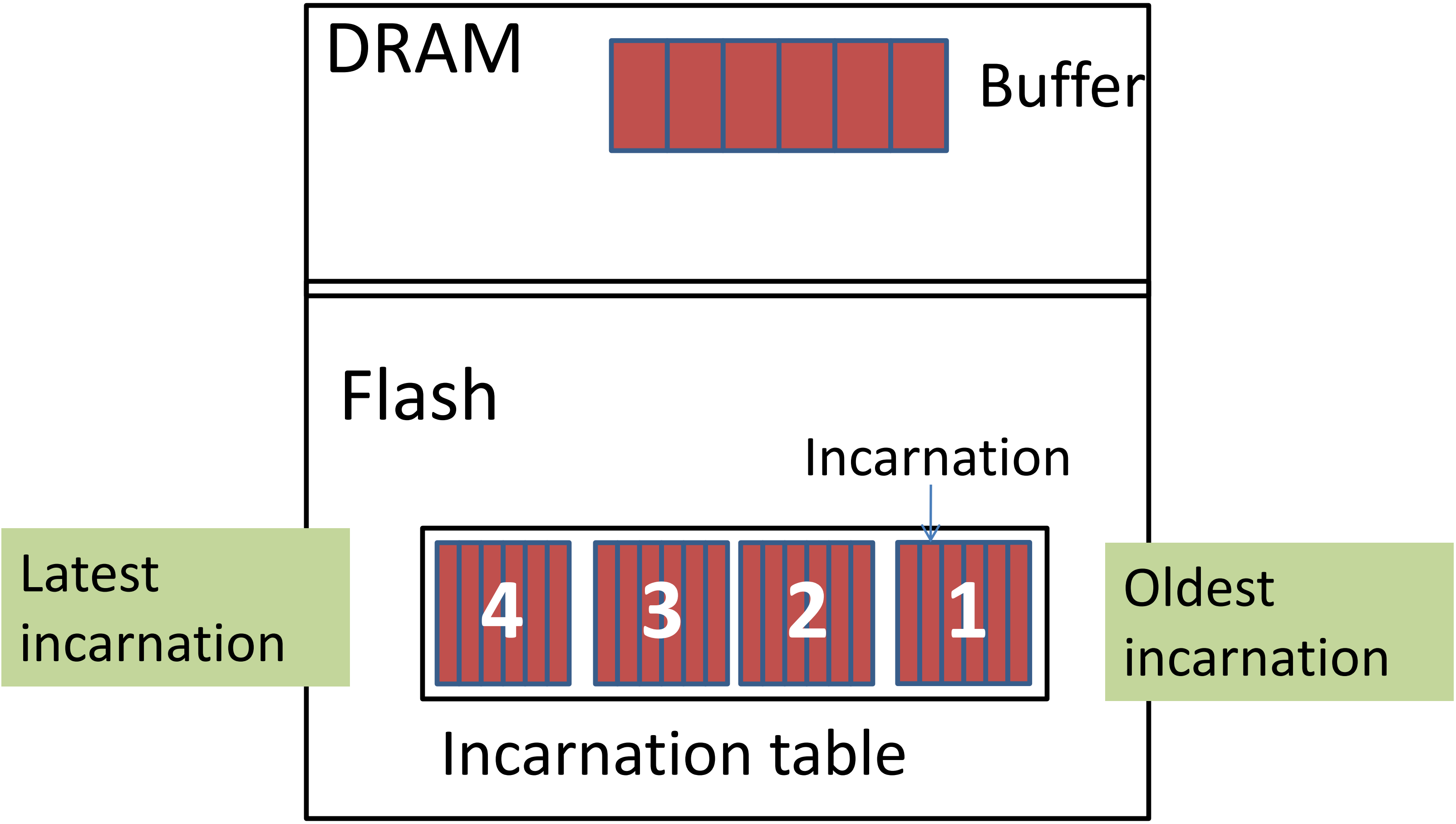
DRAM

Flash SSD

Buffer: In-memory hash table

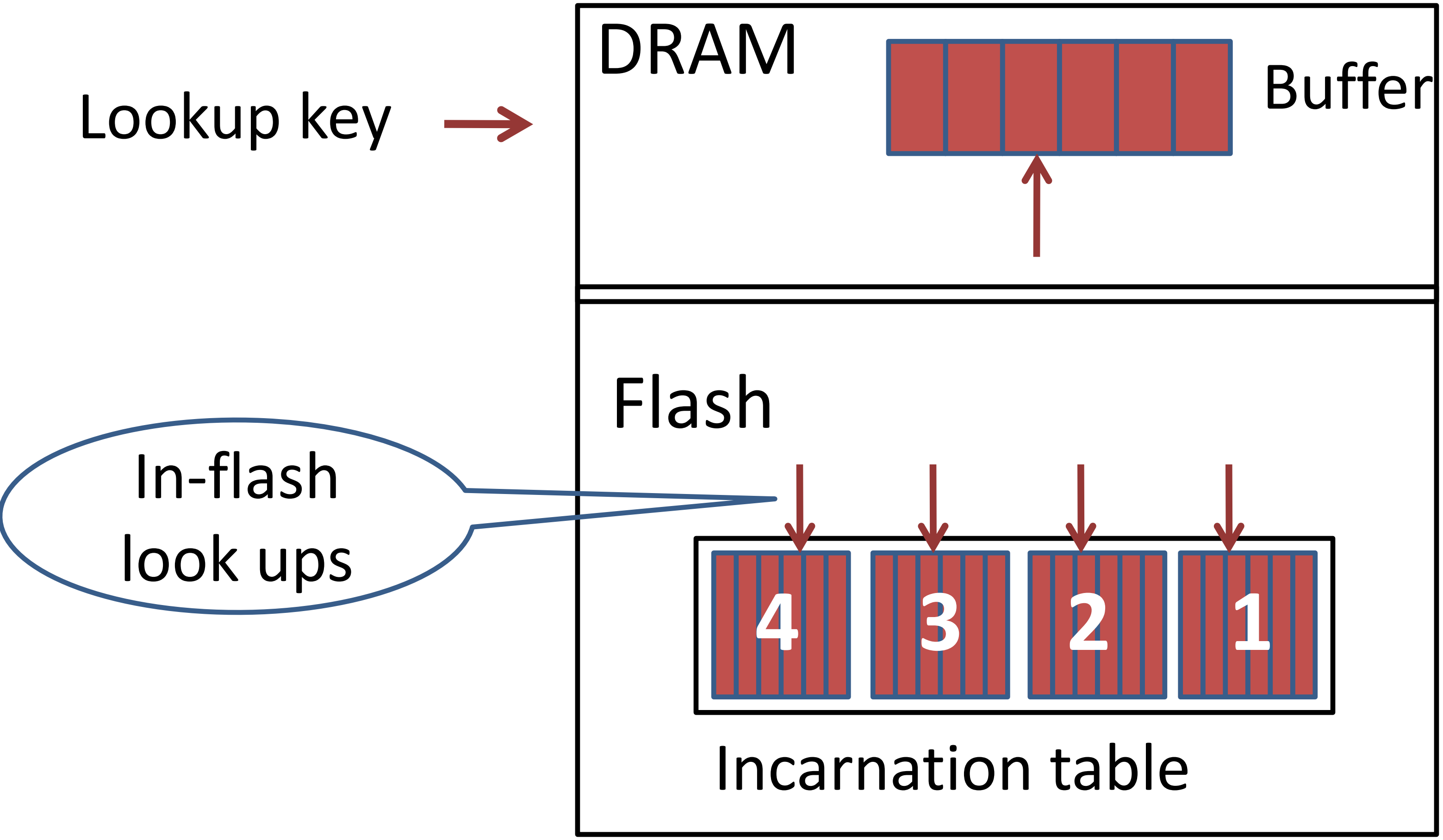
Incarnation: In-flash hash table

Two-level memory hierarchy



Net hash table is: buffer + all incarnations

Lookups are impacted due to buffers



Lookup key

DRAM

Buffer

Flash

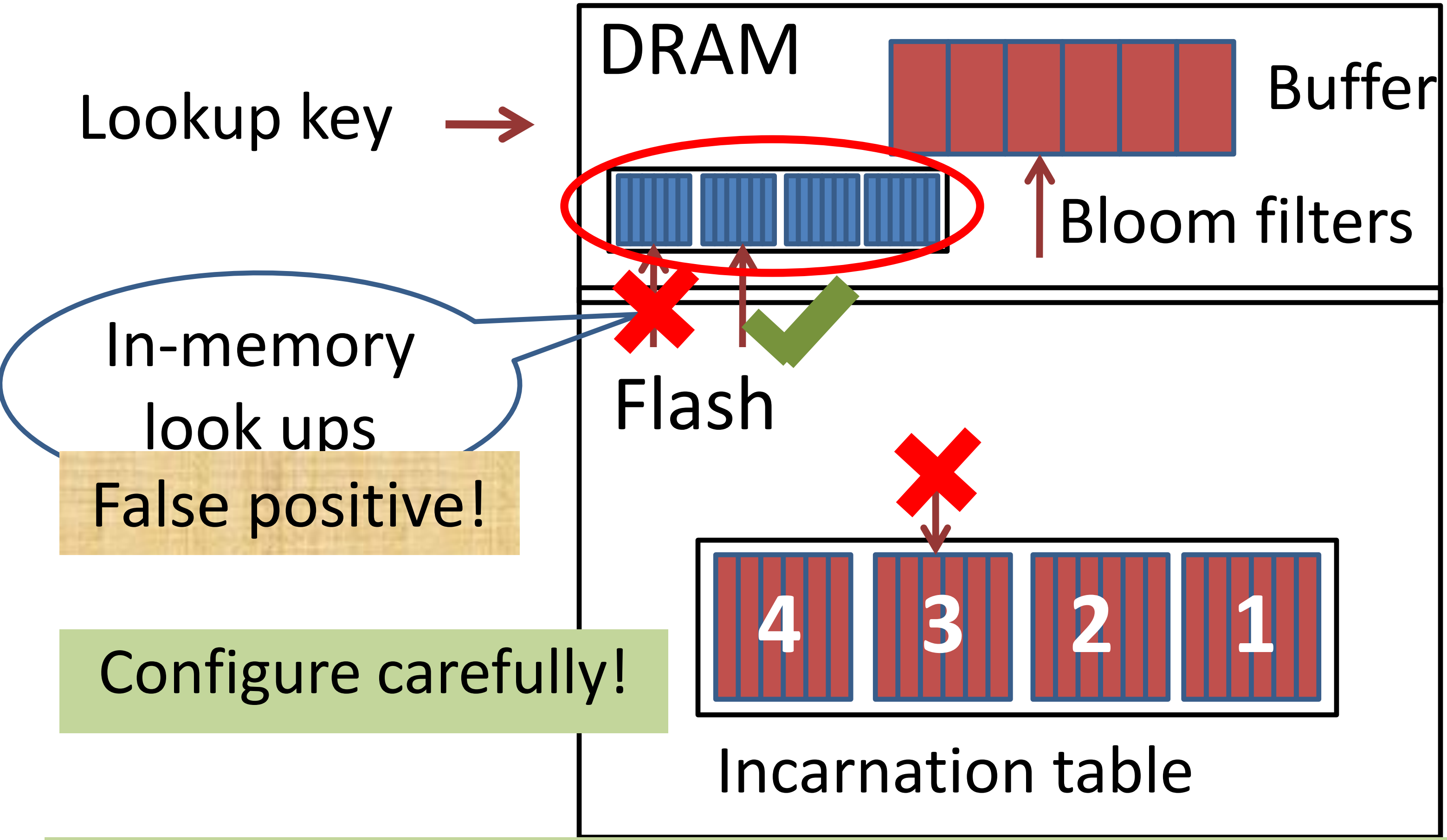
In-flash
look ups

4 3 2 1

Incarnation table

Multiple in-flash lookups. Can we limit to only one?

Bloom filters for optimizing lookups

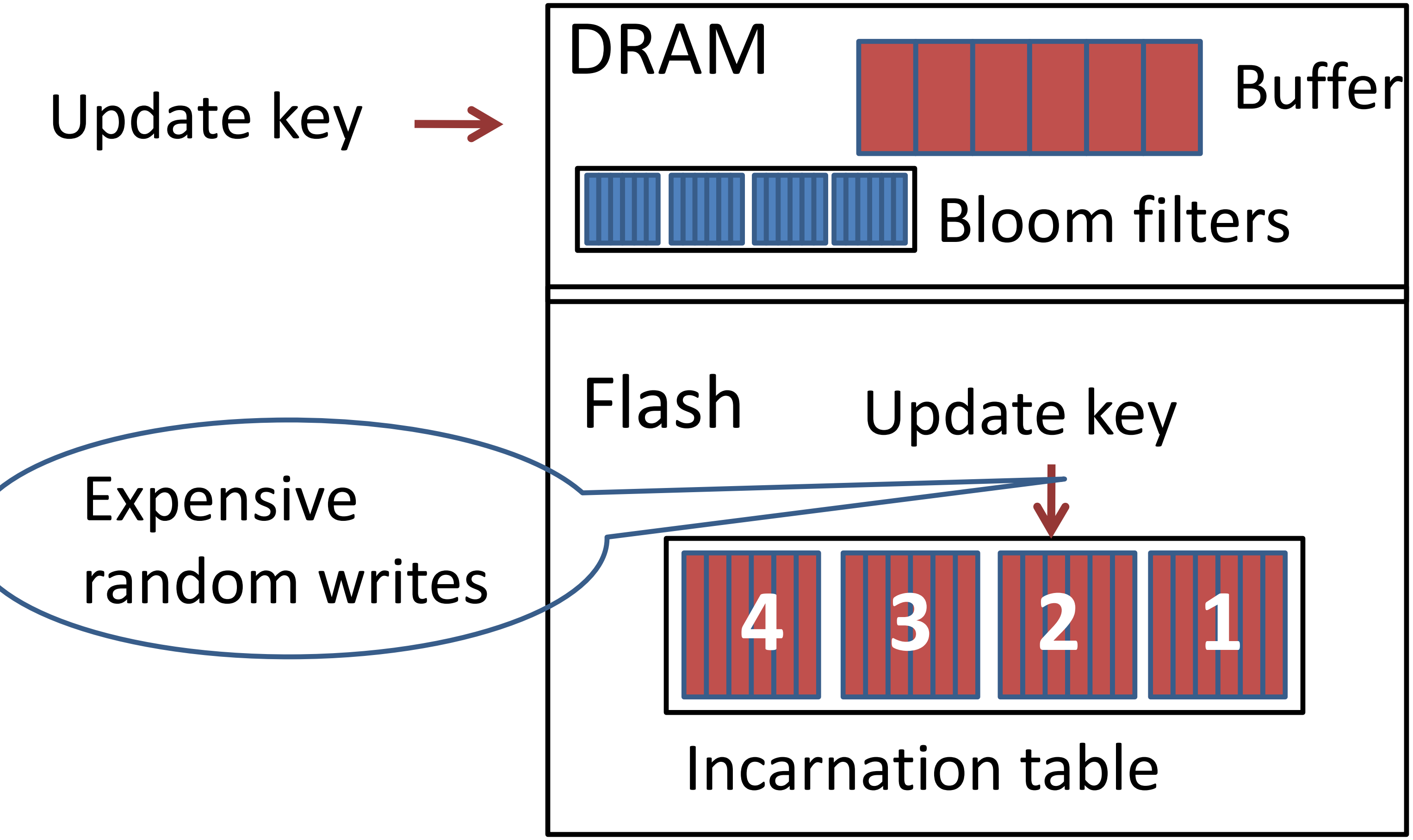


False positive!

Configure carefully!

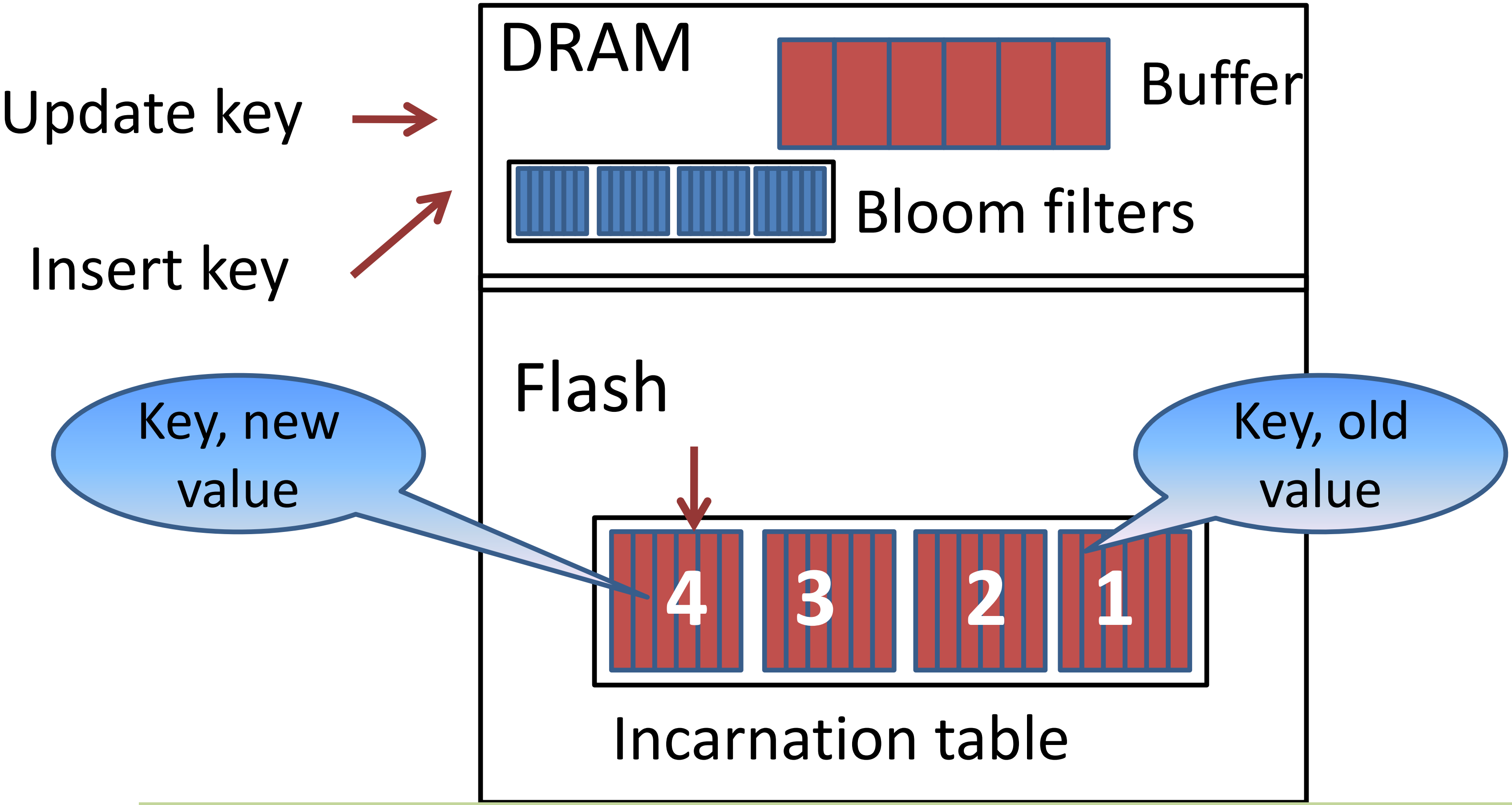
2 GB Bloom filters for 32 GB Flash for false positive rate < 0.01!

Update: naïve approach



Discard this naïve approach

Lazy updates



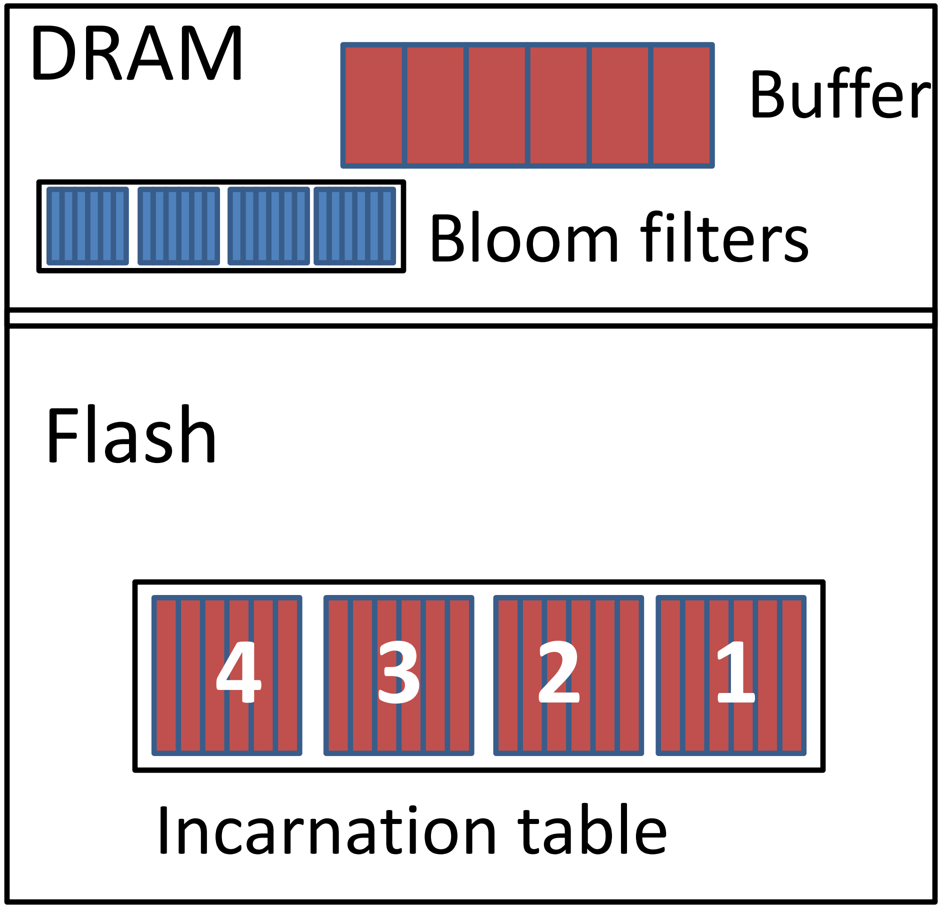
Lookups check latest incarnations first

Eviction for streaming apps

- Eviction policies may depend on application
  - LRU, FIFO, Priority based eviction, etc.
- Two BufferHash primitives
  - Full Discard: evict all items
    - Naturally implements FIFO
  - Partial Discard: retain few items
    - Priority based eviction by retaining high priority items
- BufferHash best suited for FIFO
  - Incarnations arranged by age
  - Other useful policies at some additional cost
- Details in paper

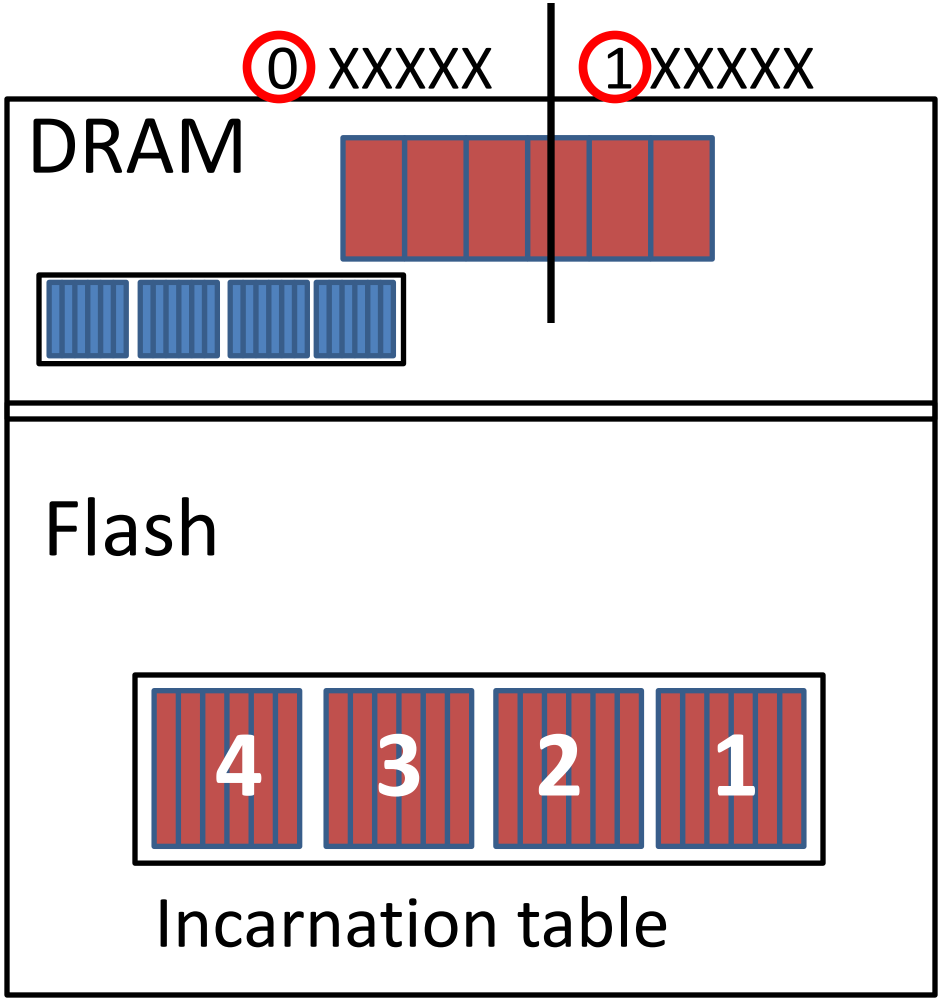
Issues with using one buffer

- Single buffer in DRAM
  - All operations and eviction policies
- High worst case insert latency
  - Few seconds for 1 GB buffer
  - New lookups stall



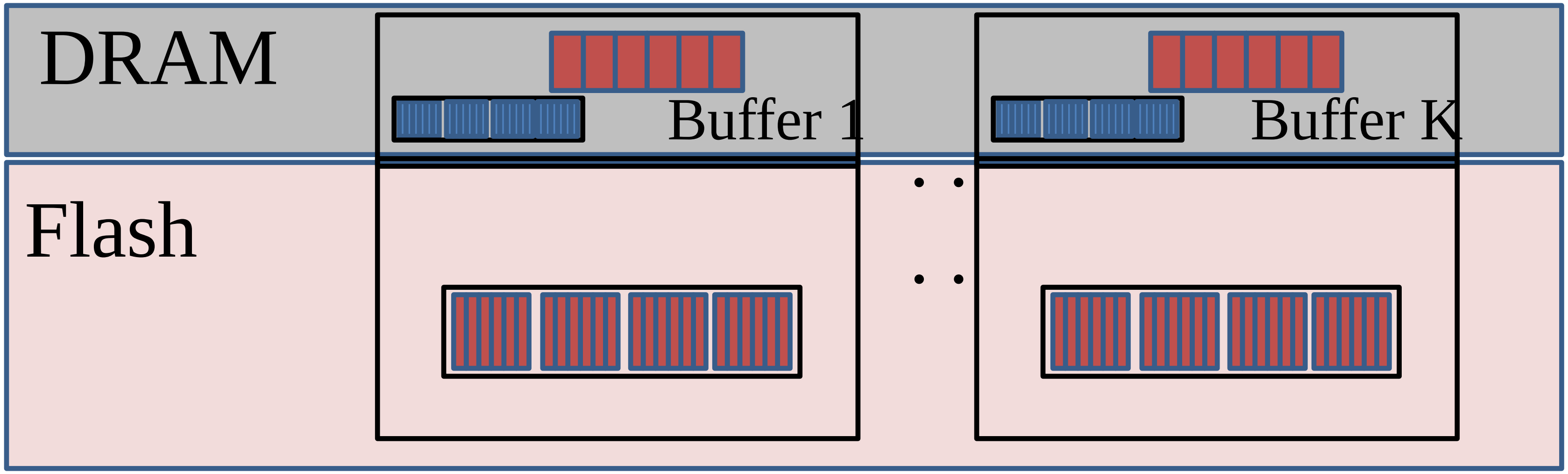
Partitioning buffers

- Partition buffers
  - Based on first few bits of key space
  - Size > page
    - Avoid i/o less than page
  - Size >= block
    - Avoid random page writes
- Reduces worst case latency
- Eviction policies apply per buffer



BufferHash: Putting it all together

- Multiple buffers in memory
- Multiple incarnations per buffer in flash
- One in-memory bloom filter per incarnation



Net hash table = all buffers + all incarnations

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  - *Latency analysis and performance tuning*

- Evaluation

Latency analysis

- Insertion latency
  - Worst case $\propto$ size of buffer
  - Average case is constant for buffer > block size

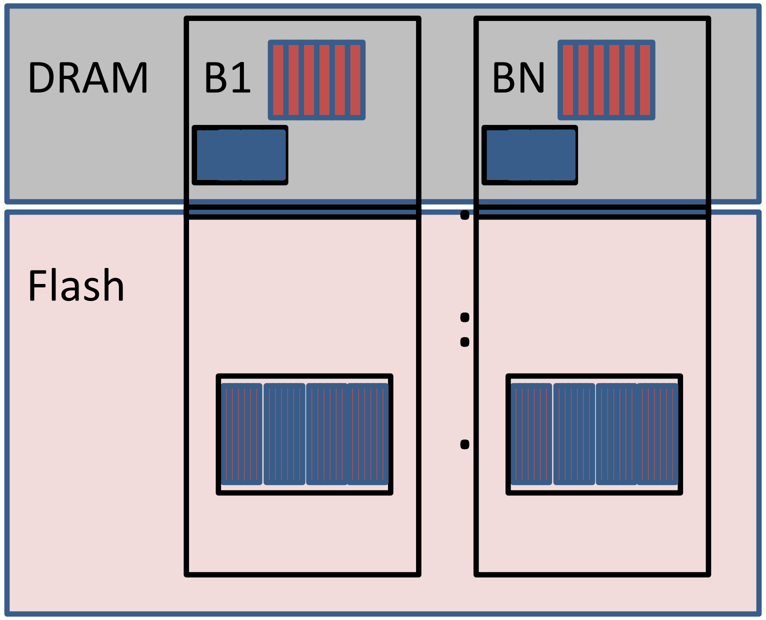
- Lookup latency
  - Average case $\propto$ Number of incarnations
  - Average case $\propto$ False positive rate of bloom filter

Parameter tuning: Total size of Buffers

Total size of buffers = B1 + B2 + … + BN

Given fixed DRAM, how much allocated to buffers

Total bloom filter size = DRAM – total size of buffers



Lookup $\propto$ #Incarnations * False positive rate

Incarnations = (Flash size/Total buffer size)

False positive rate increases as the size of bloom filters decrease

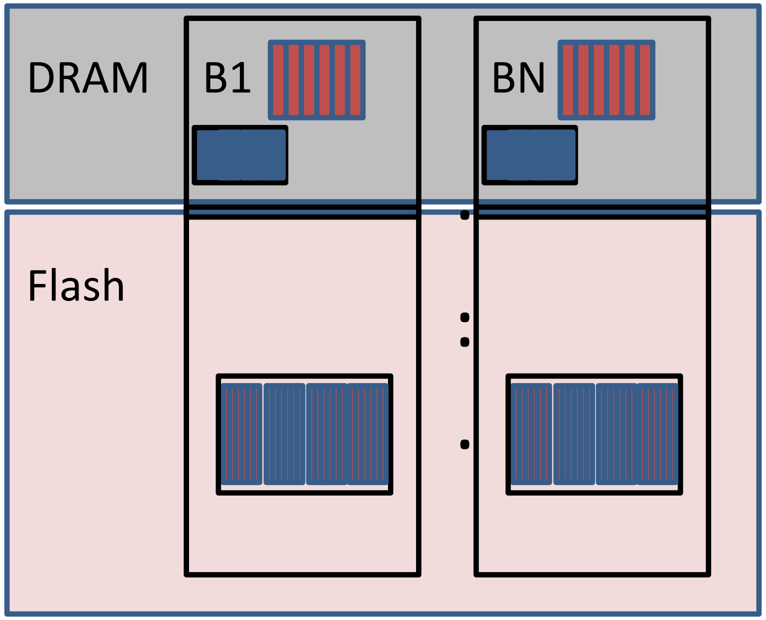
Too small is not optimal

Too large is not optimal either

Optimal = 2 * SSD/entry

Parameter tuning: Per-buffer size

What should be size of a partitioned buffer (e.g. B1) ?



Affects worst case insertion

Adjusted according to application requirement (128 KB – 1 block)

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Evaluation

- Configuration
  - 4 GB DRAM, 32 GB Intel SSD, Transcend SSD
  - 2 GB buffers, 2 GB bloom filters, 0.01 false positive rate
  - FIFO eviction policy

BufferHash performance

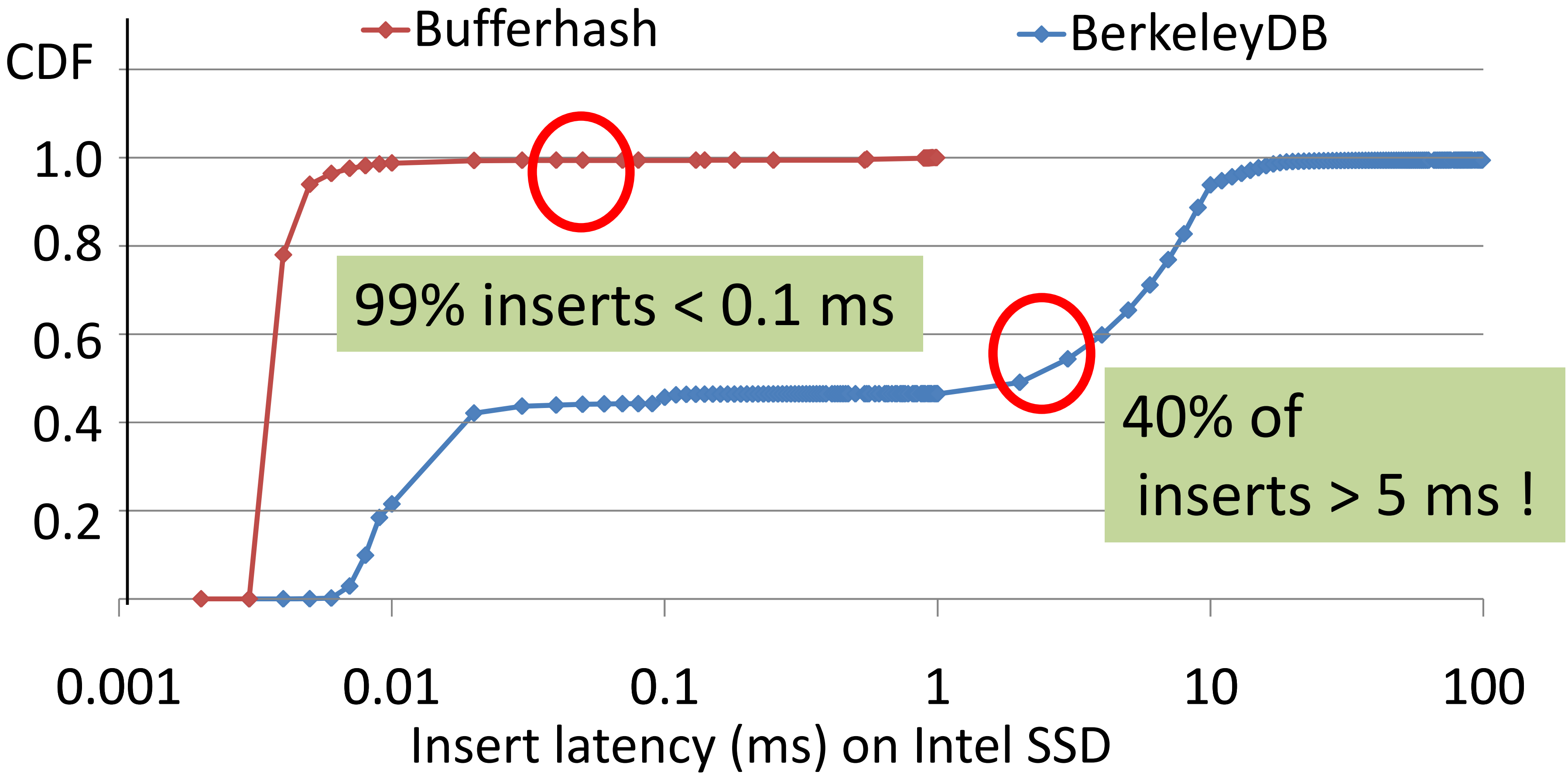
- WAN optimizer workload
  - Random key lookups followed by inserts
  - Hit rate (40%)
  - Used workload from real packet traces also
- Comparison with BerkeleyDB (traditional hash table) on Intel SSD

Average latency	BufferHash	BerkeleyDB
Look up (ms)	0.06	4.6
Insert (ms)	0.006	4.8

Better lookups!

Better inserts!

Insert performance



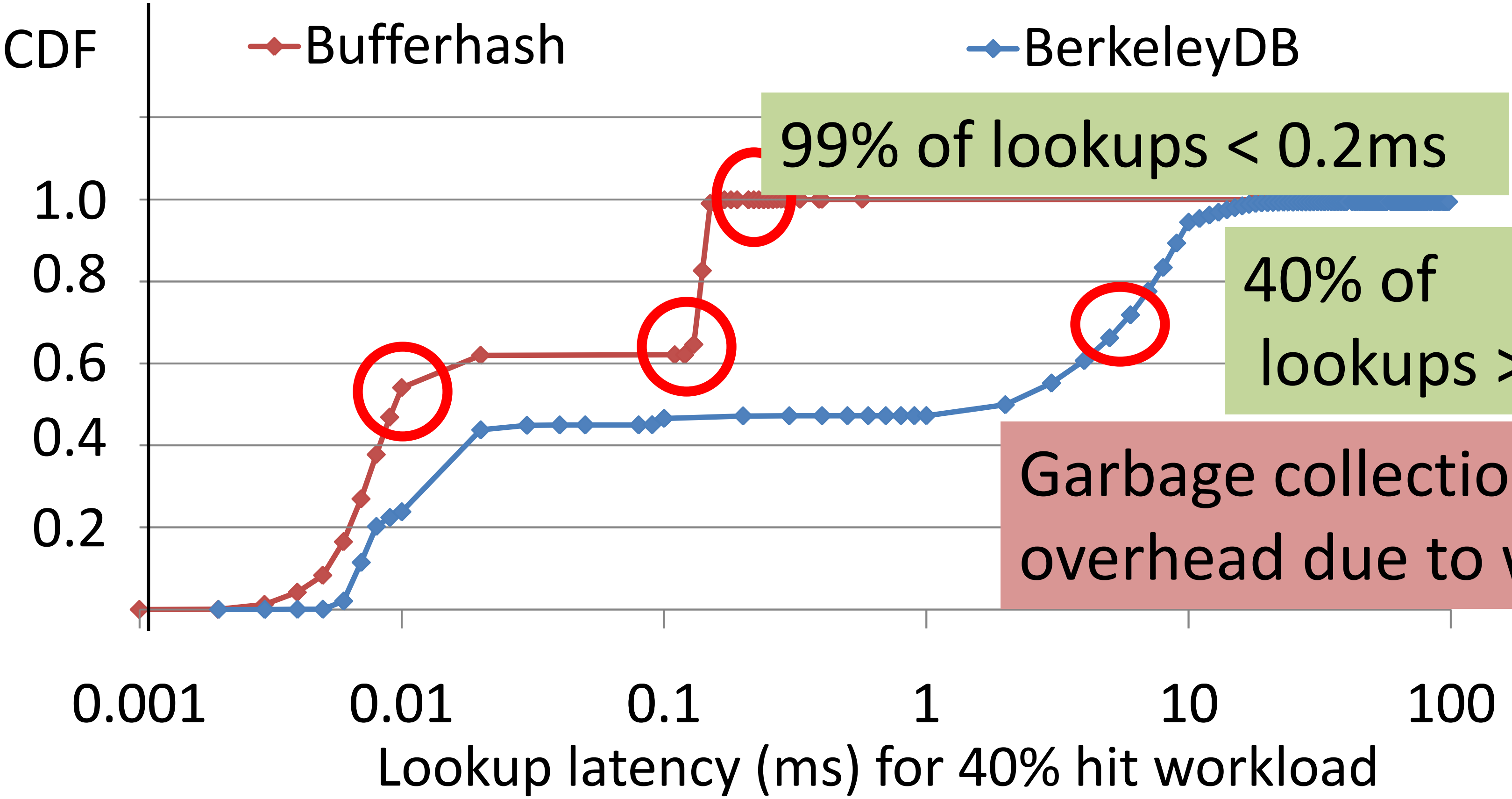
99% inserts < 0.1 ms

40% of inserts > 5 ms !

Buffering effect!

Random writes are slow!

Lookup performance



99% of lookups < 0.2ms

40% of lookups > 5 ms

Garbage collection overhead due to writes!

0.15 ms Intel SSD latency

Performance in Ops/sec/$

- 16K lookups/sec and 160K inserts/sec

- Overall cost of $400

- 42 lookups/sec/$ and 420 inserts/sec/$
  - Orders of magnitude better than 2.5 ops/sec/$ of DRAM based hash tables

Other workloads

- Varying fractions of lookups
- Results on Trancend SSD

	Average latency per operation	
Lookup fraction	**BufferHash**	**BerkeleyDB**
0	0.007 ms	18.4 ms
0.5	0.09 ms	10.3 ms
1	0.12 ms	0.3 ms

- BufferHash ideally suited for write intensive workloads

Evaluation summary

- BufferHash performs orders of magnitude better in ops/sec/$ compared to traditional hashtables on DRAM (and disks)

- BufferHash is best suited for FIFO eviction policy
  - Other policies can be supported at additional cost, details in paper

- WAN optimizer using Bufferhash can operate optimally at 200 Mbps, much better than 10 Mbps with BerkeleyDB
  - Details in paper

Related Work

- FAWN (Vasudevan et al., SOSP 2009)
  - Cluster of wimpy nodes with flash storage
  - Each wimpy node has its hash table in DRAM
  - We target…
    - *Hash table much bigger than DRAM*
    - *Low latency as well as high throughput systems*
- HashCache (Badam et al., NSDI 2009)
  - In-memory hash table for objects stored on disk

Conclusion

- We have designed a new data structure BufferHash for building CLAMs
- Our CLAM on Intel SSD achieves high ops/sec/$ for today's data-intensive systems
- Our CLAM can support useful eviction policies
- Dramatically improves performance of WAN optimizers

Thank you