Flash Memory Aware Software Architectures and Applications

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Contains work that is joint with Biplob Debnath (Univ. of Minnesota)

Flash Memory

- Used for more than a decade in consumer device storage applications
- Very recent use in desktops and servers
  - New access patterns (e.g., random writes) pose new challenges for delivering sustained high throughput and low latency
  - Higher requirements in reliability, performance, data life
- Challenges being addressed at different layers of storage stack
  - Flash device vendors: device driver/ inside device
  - System builders: OS and application layers, e.g., Focus of this talk

Flash Aware Applications

- System builders: Don't just treat flash as disk replacement
  - Make the OS/application layer aware of flash
  - Exploit its benefits
  - Embrace its peculiarities and design around them
  - Identify applications that can exploit sweet spot between cost and performance
- Device vendors: You can help by exposing more APIs to the software layer for managing storage on flash
  - Can help to squeeze better performance out of flash with application knowledge

Flash for Speeding Up Cloud/Server Applications

- FlashStore [VLDB 2010]
  - High throughput, low latency persistent key-value store using flash as cache above HDD
- ChunkStash [USENIX ATC 2010]
  - Efficient index design on flash for high throughput data deduplication
- BloomFlash [ICDCS 2011]
  - Bloom filter design for flash
- SkimpyStash [ACM SIGMOD 2011]
  - Key-value store with ultra-low RAM footprint at about 1-byte per k-v pair
- Flash as block level cache above HDD
  - Either application managed or OS managed
  - SSD buffer pool extension in database server
  - SSD caching tier in cloud storage

Flash Memory: Random Writes

- Need to optimize the storage stack for making best use of flash
  - Random writes not efficient on flash media
  - Flash Translation Layer (FTL) cannot hide or abstract away device constraints

FusionIO 160GB ioDrive

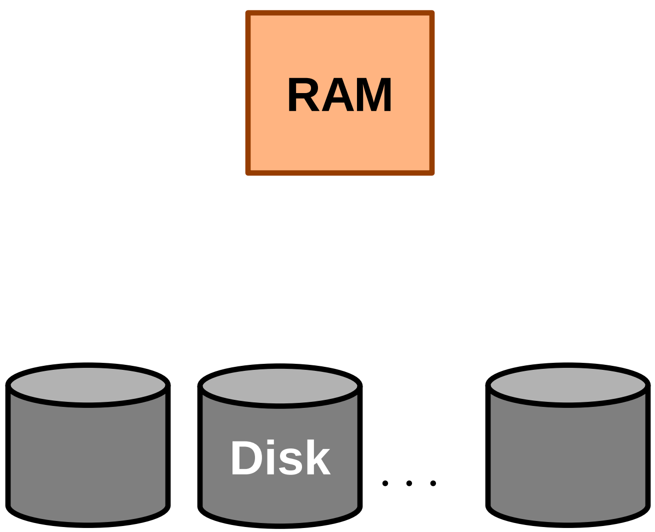
FlashStore: High Throughput Persistent Key-Value Store

Design Goals and Guidelines

- Support low latency, high throughput operations as a key-value store
- Exploit flash memory properties and work around its constraints
  - Fast random (and sequential) reads
  - Reduce random writes
  - Non-volatile property
- Low RAM footprint per key independent of key-value pair size

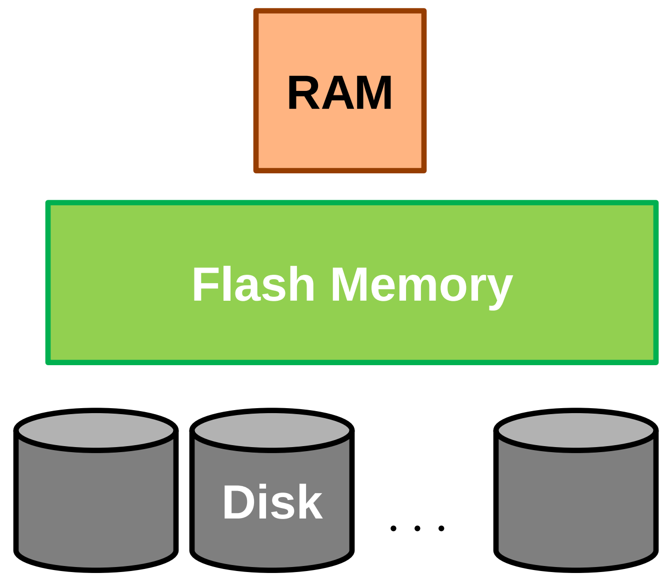
FlashStore Design: Flash as Cache

- Low-latency, high throughput operations
- Use flash memory as cache between RAM and hard disk



Current

(bottlenecked by hard disk seek times ~ 10msec)

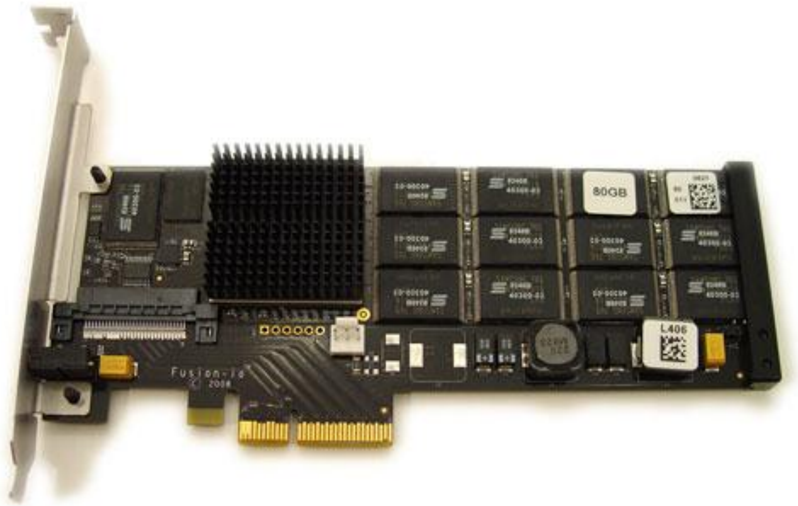


FlashStore

(flash access times are of the order of 10 -100 µsec)

FlashStore Design: Flash Awareness

- Flash aware data structures and algorithms
  - Random writes, in-place updates are expensive on flash memory
    - Flash Translation Layer (FTL) cannot hide or abstract away device constraints
  - Sequential writes, Random/Sequential reads great!
- Use flash in a log-structured manner

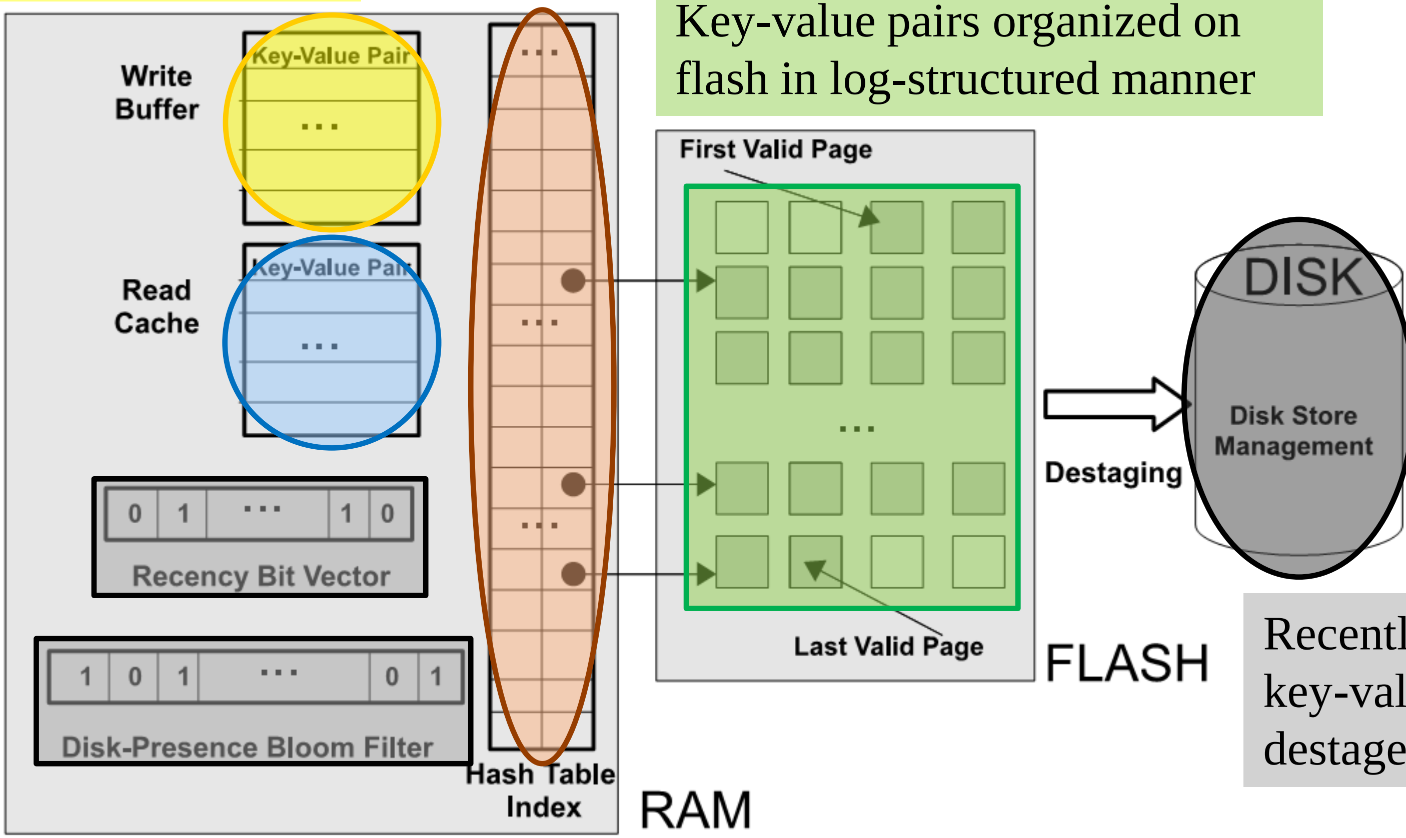


FusionIO 160GB ioDrive

FlashStore Architecture

RAM write buffer for aggregating writes into flash

Key-value pairs organized on flash in log-structured manner



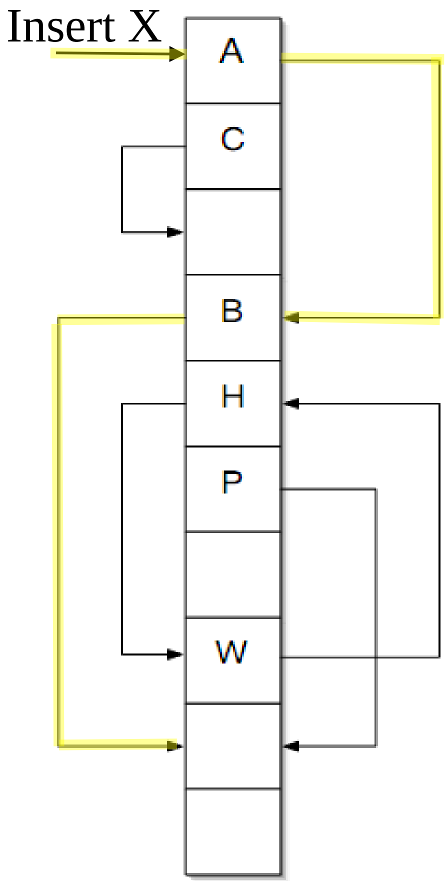
Recently unused key-value pairs destaged to HDD

RAM read cache for recently accessed key-value pairs

Key-value pairs on flash indexed in RAM using a specialized space efficient hash table

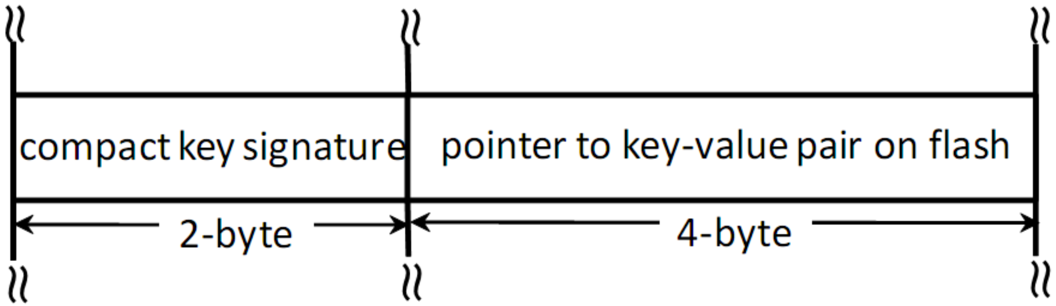
FlashStore Design: Low RAM Usage

- High hash table load factors while keeping lookup times fast
  - Collisions resolved using cuckoo hashing
  - Key can be in one of K candidate positions
  - Later inserted keys can relocate earlier keys to their other candidate positions
  - K candidate positions for key x obtained using K hash functions $h_1(x)$, …, $h_K(x)$
  - In practice, two hash functions can simulate K hash functions using $h_i(x) = g_1(x) + i*g_2(x)$
- System uses value of K=16 and targets 90% hash table load factor



Low RAM Usage: Compact Key Signatures

- Compact key signatures stored in hash table
  - 2-byte key signature (vs. key length size bytes)
  - Key x stored at its candidate position i derives its signature from $h_i(x)$
  - False flash read probability < 0.01%
- Total 6-10 bytes per entry (4-8 byte flash pointer)



- Related work on key-value stores on flash media
  - MicroHash, FlashDB, FAWN, BufferHash

FlashStore Performance Evaluation

- Hardware Platform
  - Intel Processor, 4GB RAM, 7200 RPM Disk, fusionIO SSD
  - Cost without flash = $1200
  - Cost of fusionIO 80GB SLC SSD = $2200 (circa 2009)

CPU		RAM		Flash (SSD)			Hard Disk (HDD)			Chassis
Type	Power	Size	Power	Type	Cost	Power	Type	Cost	Power	Cost
Intel Core 2 Duo E8500 @3.16GHz	65W	4GB	3.5W	fusionIO 80GB	$2200	15W	Seagate Barracuda 250GB 7200rpm	$50	12W	$1150

- Trace
  - Xbox LIVE Primetime
  - Storage Deduplication

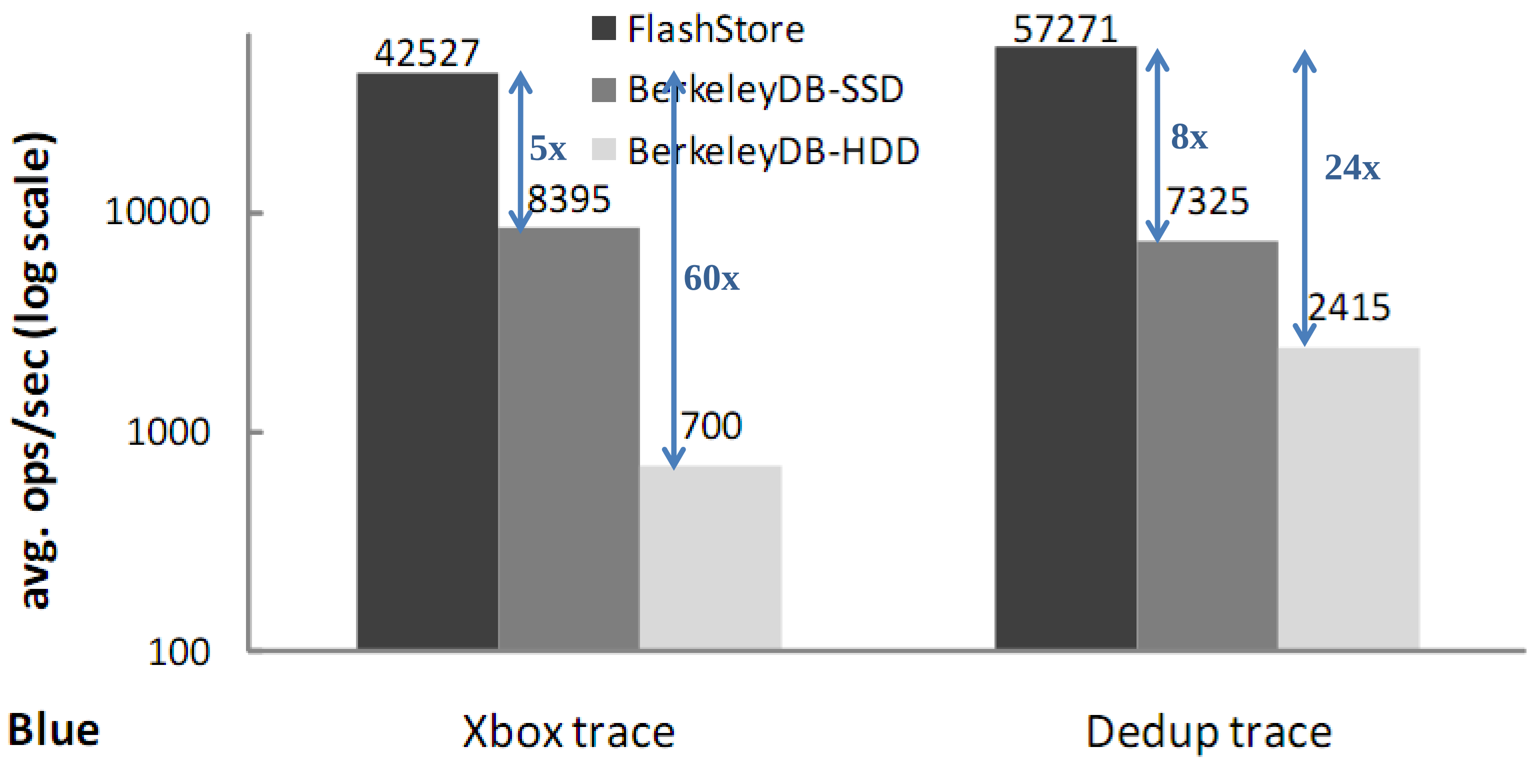
Trace	Total get-set ops	get:set ratio	Avg. size (bytes)	
			Key	Value
Xbox	5.5 million	7.5:1	92	1200
Dedup	40 million	2.2:1	20	44

FlashStore Performance Evaluation

- How much better than simple hard disk replacement with flash?
  - Impact of flash aware data structures and algorithms in FlashStore
- Comparison with flash unaware key-value store
  - FlashStore-SSD
  - BerkeleyDB-HDD
  - BerkeleyDB-SSD
  - FlashStore-SSD-HDD (evaluate impact of flash recycling activity)

BerkeleyDB used as the flash unaware index on HDD/SSD

Throughput (get-set ops/sec)



Performance per Dollar

- From BerkeleyDB-HDD to FlashStore-SSD
  - Throughput improvement of ~ 40x
  - Flash investment = 50% of HDD capacity (example)

    = 5x of HDD cost (assuming flash costs 10x per GB)
  - Throughput/dollar improvement of about 40/6 ~ 7x

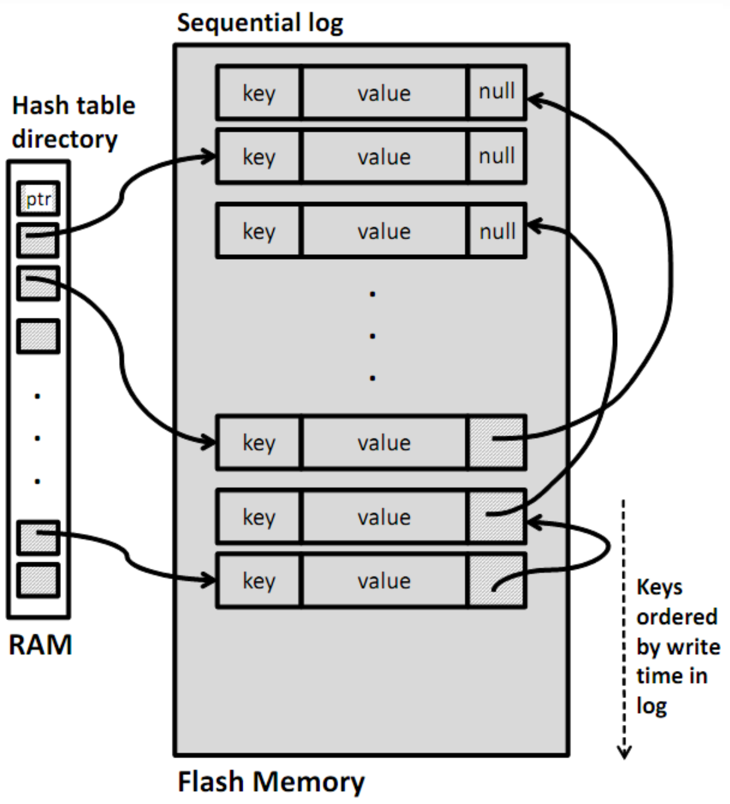
SkimpyStash: Ultra-Low RAM Footprint Key-Value Store on Flash

Aggressive Design Goal for RAM Usage

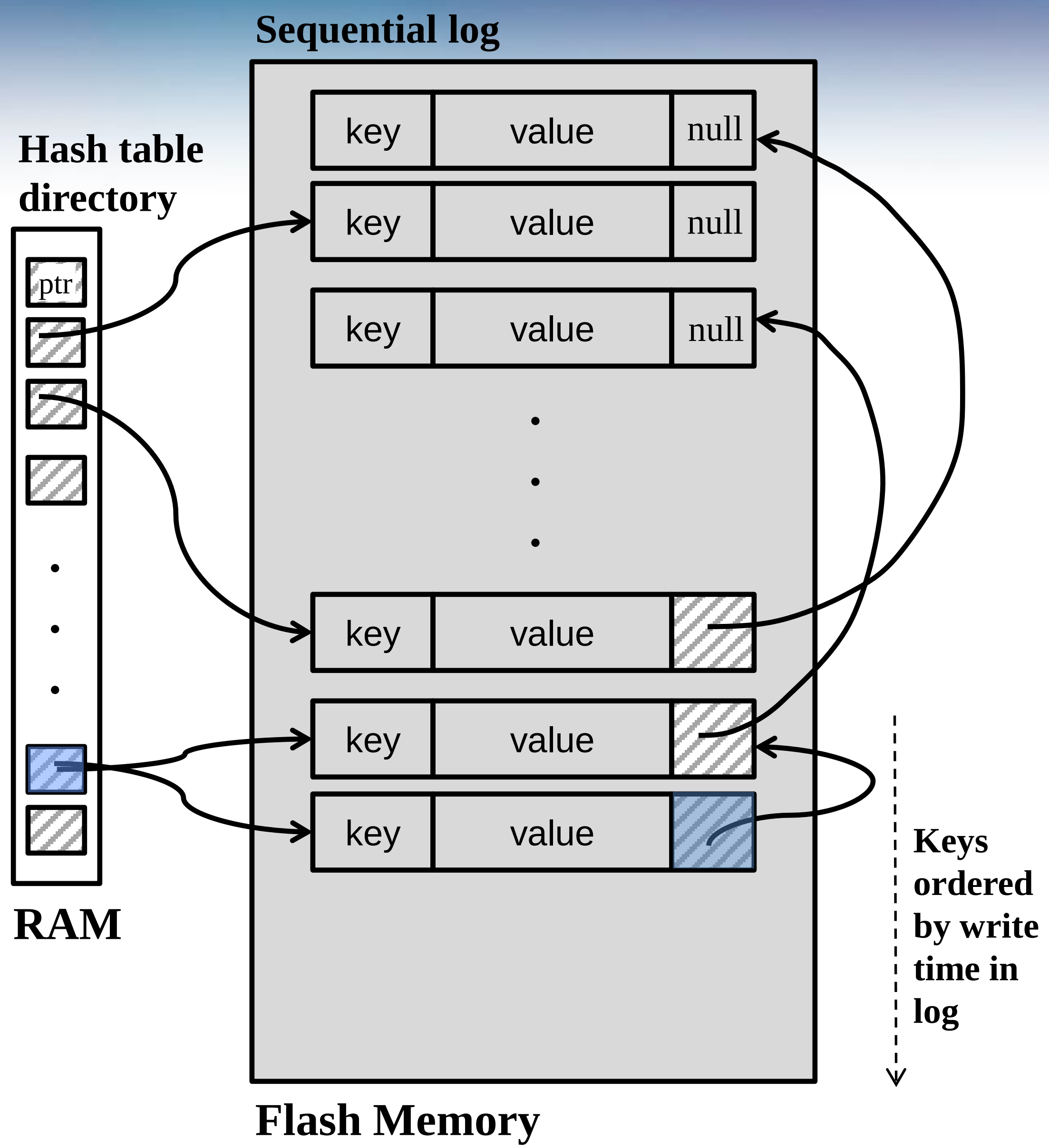
- Target ~1 byte of RAM usage per key-value pair on flash
  - Tradeoff with key access time (#flash reads per lookup)
- Preserve log-structured storage organization on flash

SkimpyStash: Base Design

- Resolve hash table collisions using linear chaining
  - Multiple keys resolving to a given hash table bucket are chained in a linked list
- Storing the linked lists on flash itself
  - Preserve log-structured organization with later inserted keys pointing to earlier keys in the log



  - Each hash table bucket in RAM contains a pointer to the beginning of the linked list on flash


Sequential log
Hash table directory
ptr
key
value
null
key
value
null
key
value
null
key
value
key
value
key
value
RAM
Keys ordered by write time in log
Flash Memory

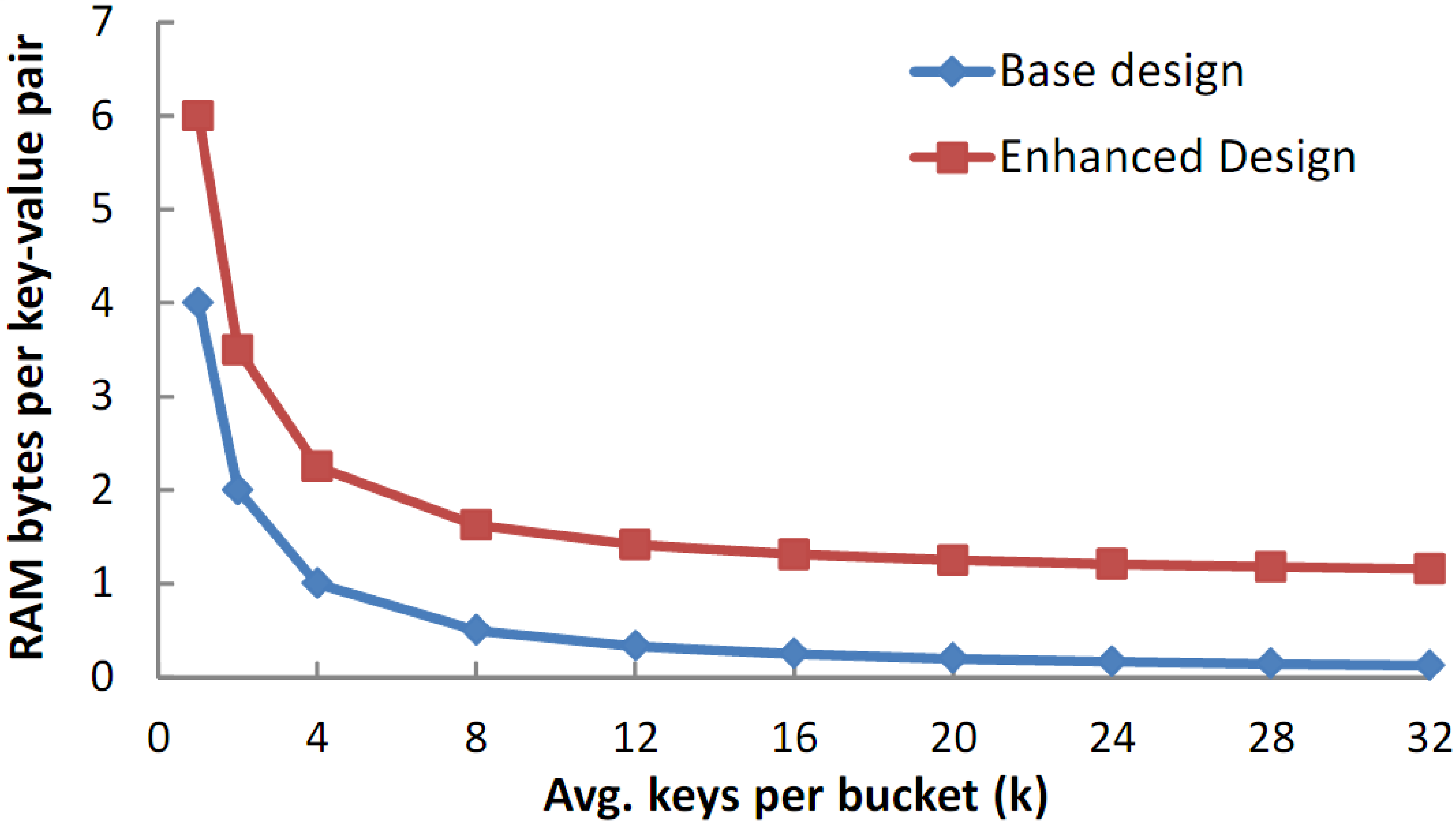
SkimpyStash: Page Layout on Flash

- Logical pages are formed by linking together records on possibly different physical pages
  - Hash buckets do ***not*** correspond to whole physical pages on flash but to logical pages
  - Physical pages on flash contain records from multiple hash buckets
- Exploits random access nature of flash media
  - No disk-like seek overhead in reading records in a hash bucket spread across multiple physical pages on flash

Base Design: RAM Space Usage

- k = average #keys per bucket
  - Critical design parameter
- (4/k) bytes of RAM per k-v pair
  - Pointer to chain on flash (4 bytes) per slot
- Example: k=10
  - Average of 5 flash reads per lookup = ~50 usec
  - 0.5 bytes in RAM per k-v pair on flash

The Tradeoff Curve

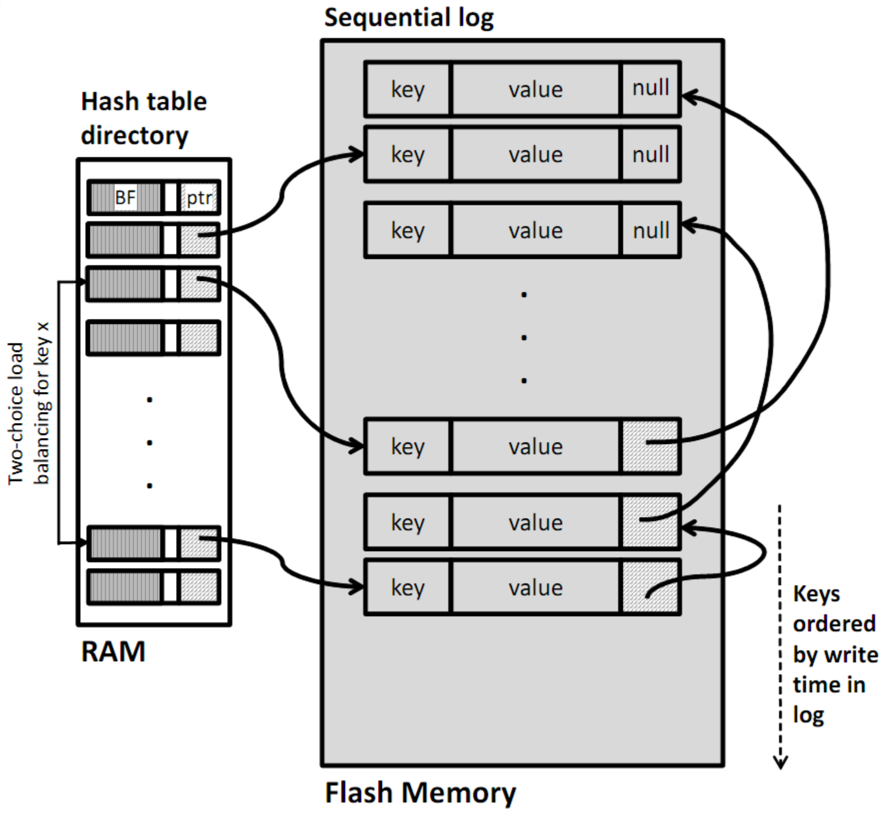


Base Design: Room for Improvement?

- Large variations in average lookup times across buckets
  - Skewed distribution in number of keys in each bucket chain
- Lookups on non-existing keys
  - Require entire bucket (linked list) to be searched on flash

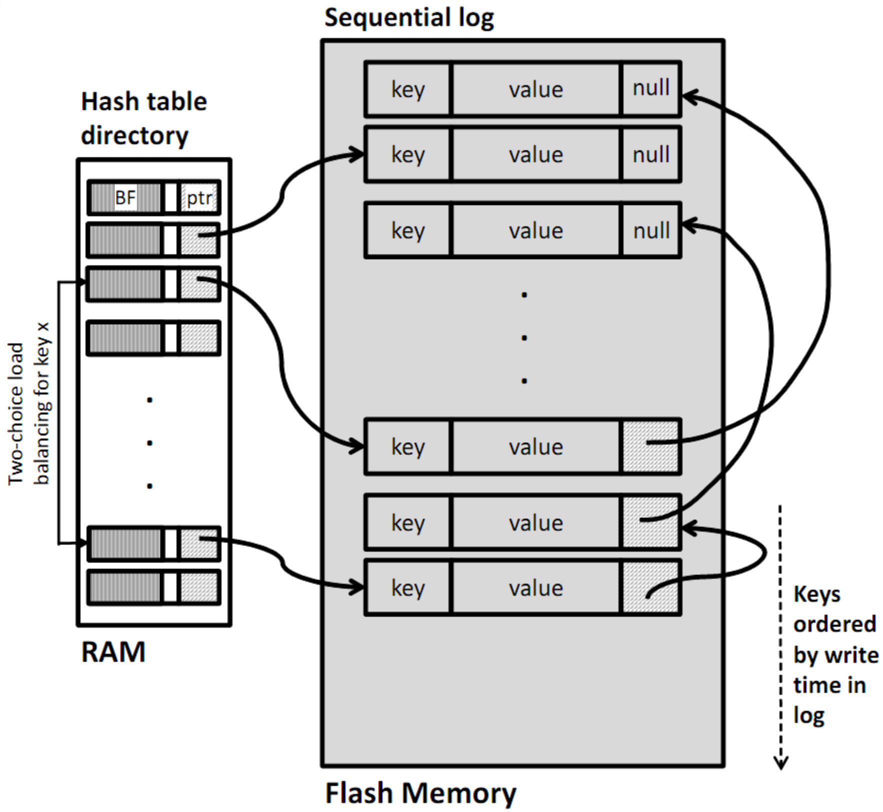
Improvement Idea 1: Load Balancing across Buckets

- Two-choice based load balancing across buckets
  - Hash each key to two buckets and insert in least-loaded bucket
  - 1-byte counter per bucket
- Lookup times double
  - Need to search both buckets during lookup
  - Fix?



Improvement Idea 2: Bloom Filter per Bucket

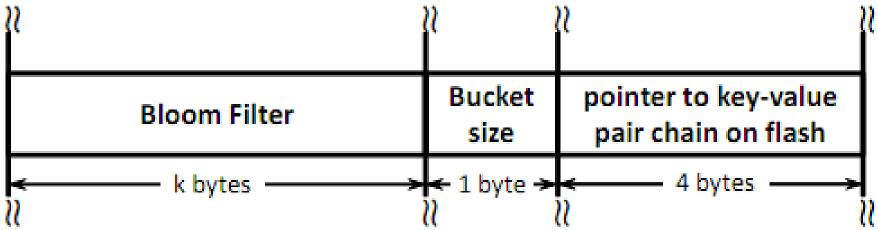
- Bloom Filter per Bucket
  - Lookup checks BF before searching linked list on flash
  - Sized for ~k keys => k-bytes per hash table directory slot
- Other benefits
  - Lookups on non-existing keys faster (almost always no flash access)
- Benefits from load balancing
  - Balanced chains help to improve BF accuracy (false positives)
  - Symbiotic relationship!



Enhanced Design: RAM Space Usage

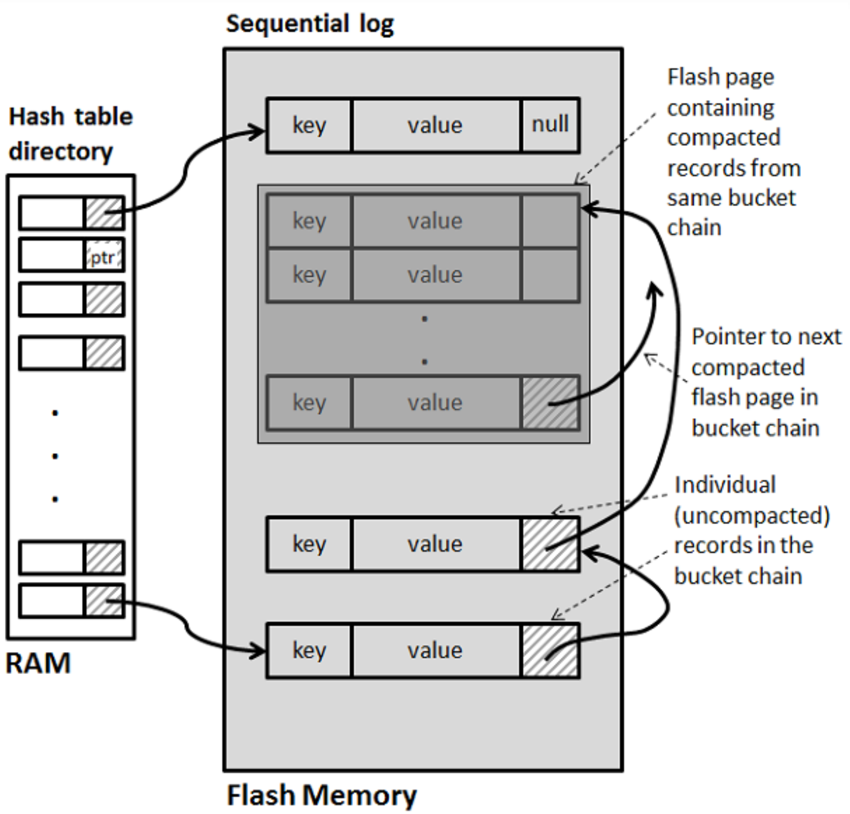
- k = average #keys per bucket
- (1 + 5/k) bytes of RAM per k-v pair
  - Pointer to chain on flash (4 bytes)
  - Bucket size (1 byte)
  - Bloom filter (k bytes)
- Example: k=10
  - Average of 5 flash reads per lookup = ~50 usec
  - 1.5 bytes in RAM per k-v pair on flash

Hash Table Directory Slot



Compaction to Improve Read Performance

- When enough records accumulate in a bucket to fill a flash page
  - Place them contiguously on one or more flash pages (m records per page)
  - Average #flash reads per lookup = ⌈k/2m⌉
- Garbage created in the log
  - Compaction
  - Updated or deleted records

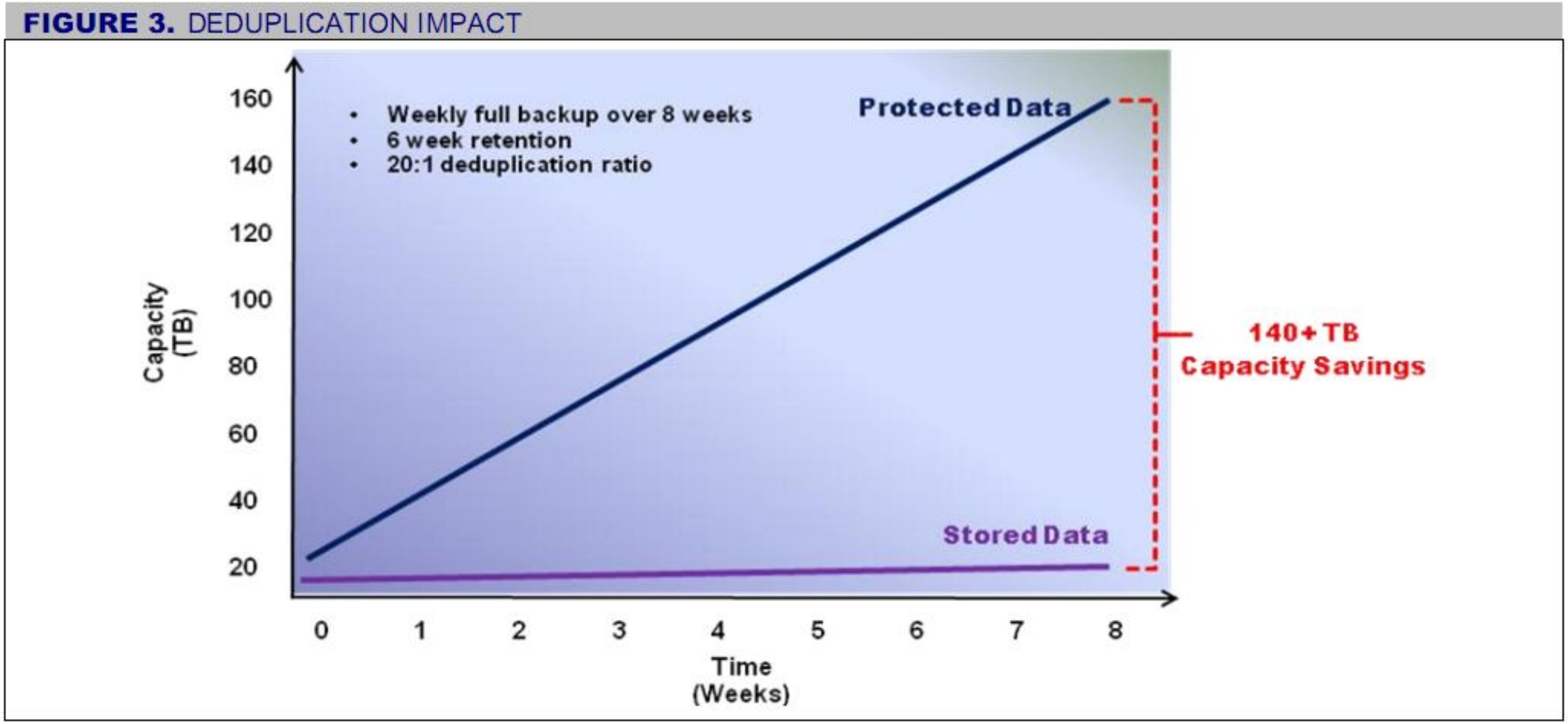


ChunkStash: Speeding Up Storage Deduplication using Flash Memory

Deduplication of Storage

- Detect and remove duplicate data in storage systems
  - e.g., Across multiple full backups
  - Storage space savings
  - Faster backup completion: Disk I/O and Network bandwidth savings
- Feature offering in many storage systems products
  - Data Domain, EMC, NetApp
- Backups need to complete over windows of few hours
  - Throughput (MB/sec) important performance metric
- High-level techniques
  - Content based chunking, detect/store unique chunks only
  - Object/File level, Differential encoding

Impact of Dedup Savings Across Full Backups



Source: Data Domain white paper

Content based Chunking

- Calculate Rabin fingerprint hash for each sliding window (16 byte)

101 100 000 001 010 101 010 010 010 110
010 101 000 010 010 010 101 101 100 101

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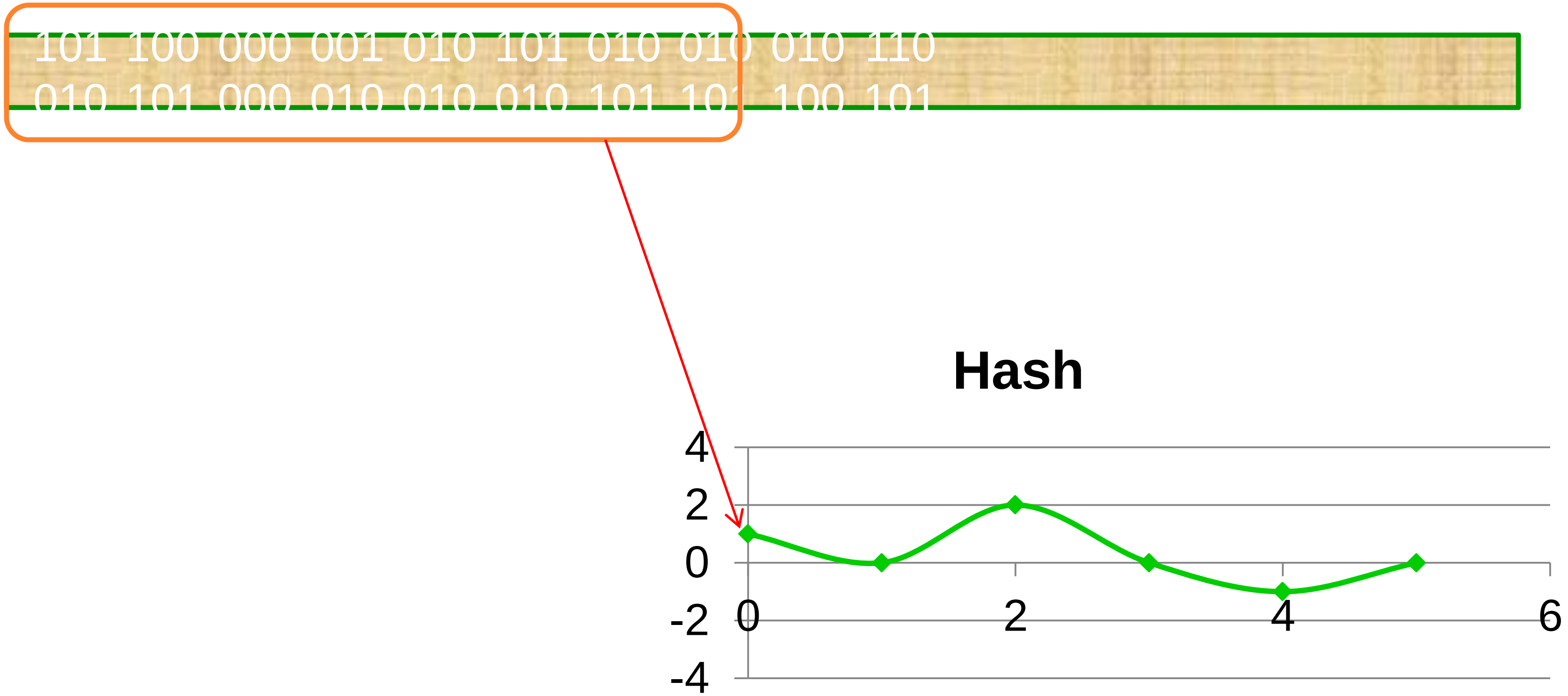

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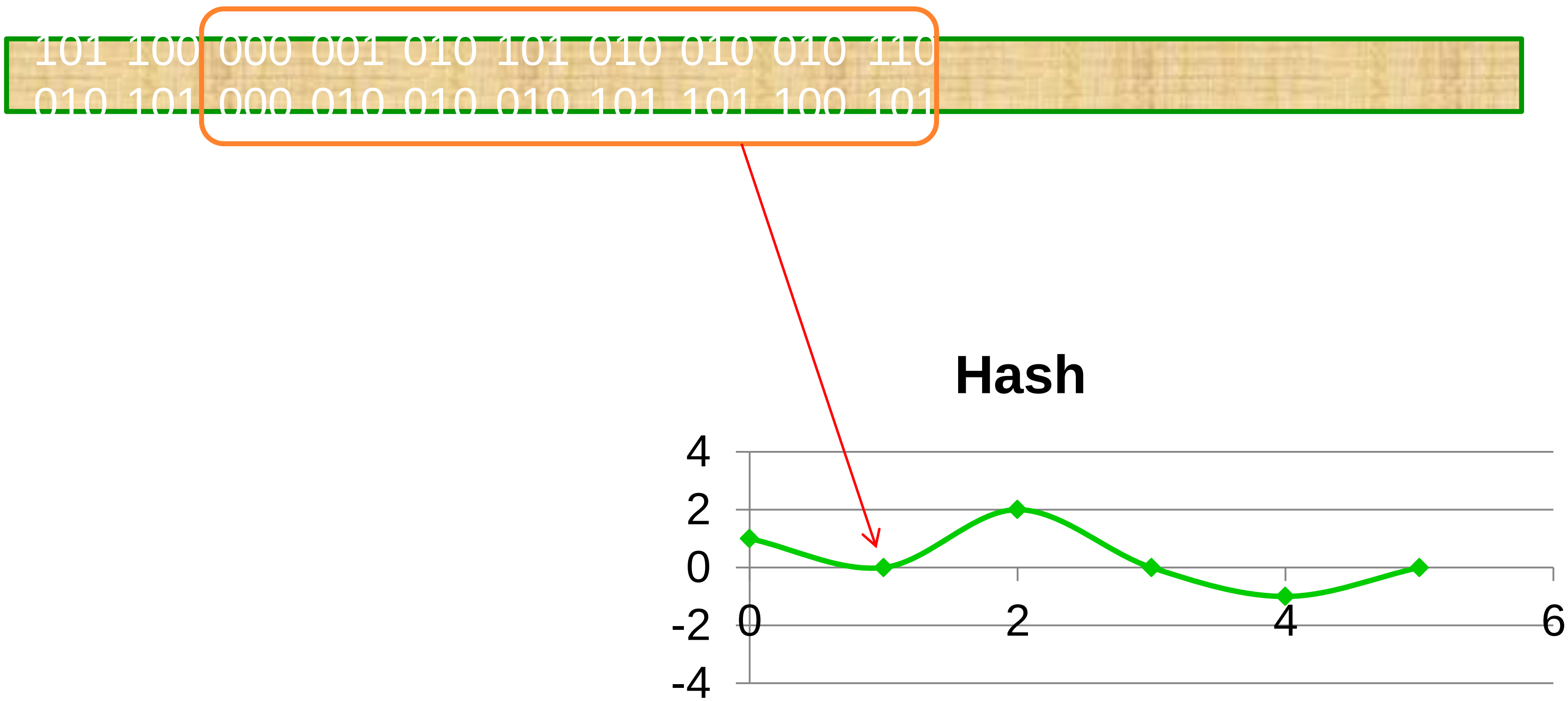

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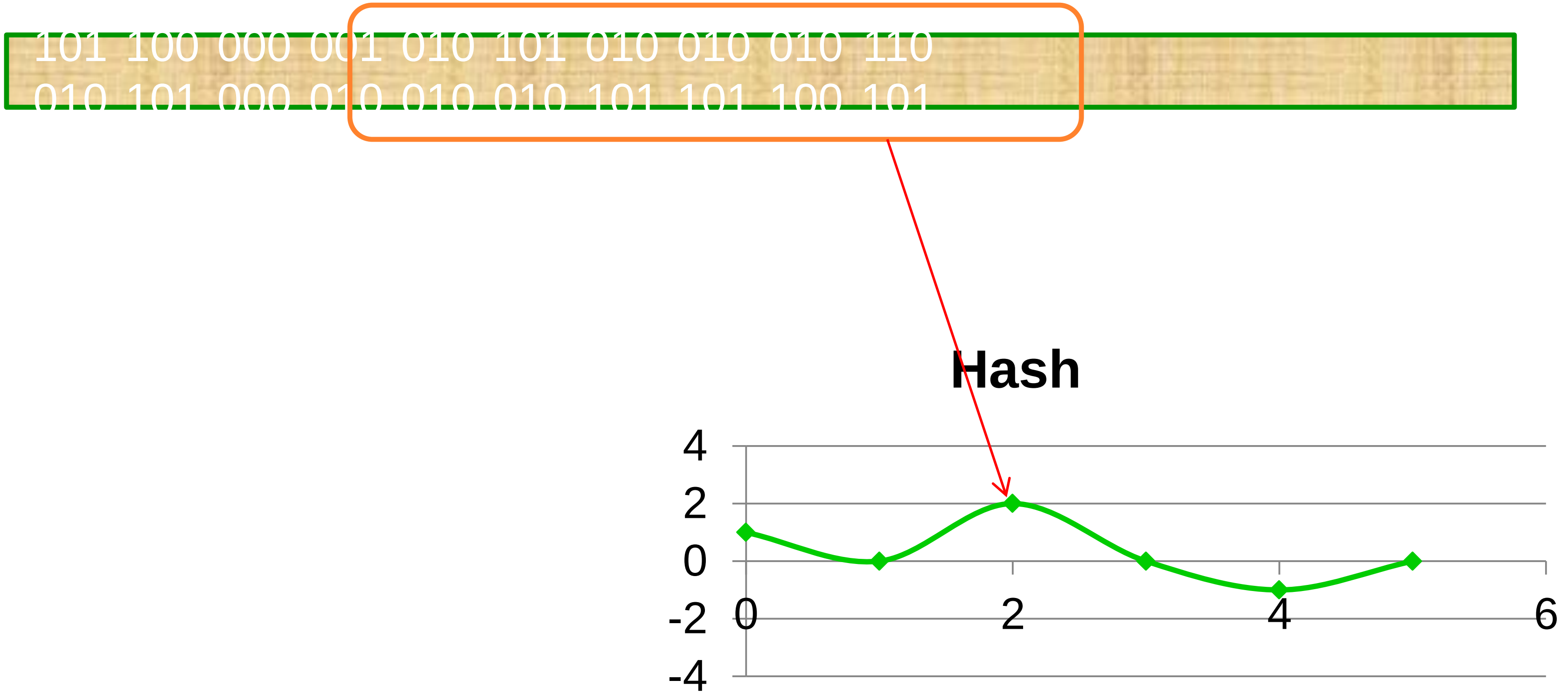

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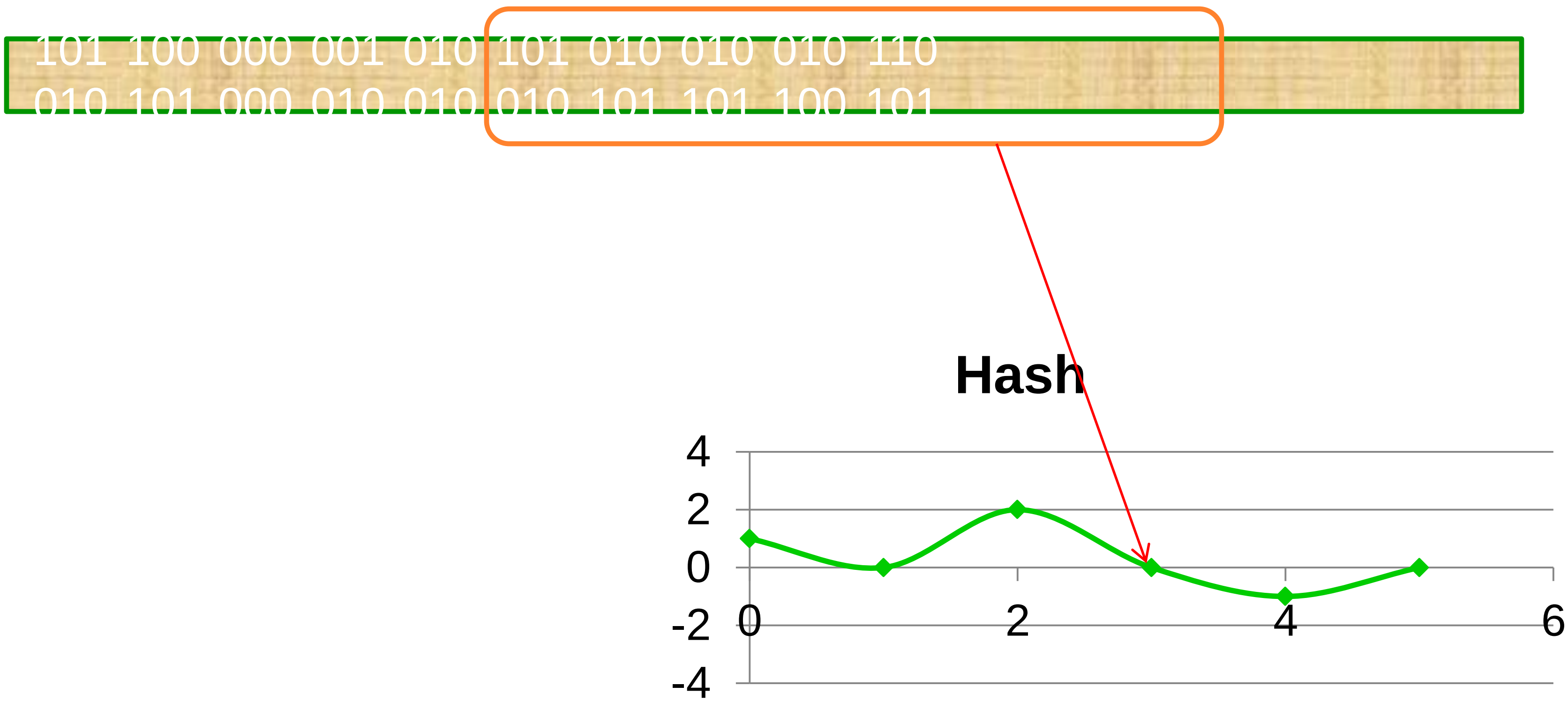

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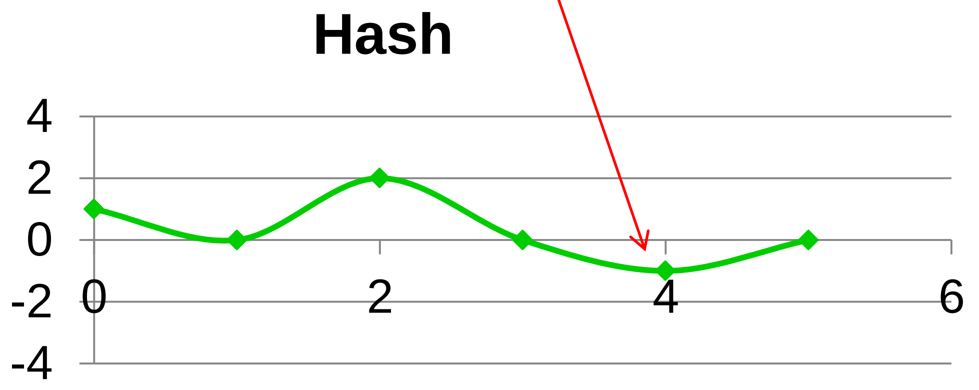

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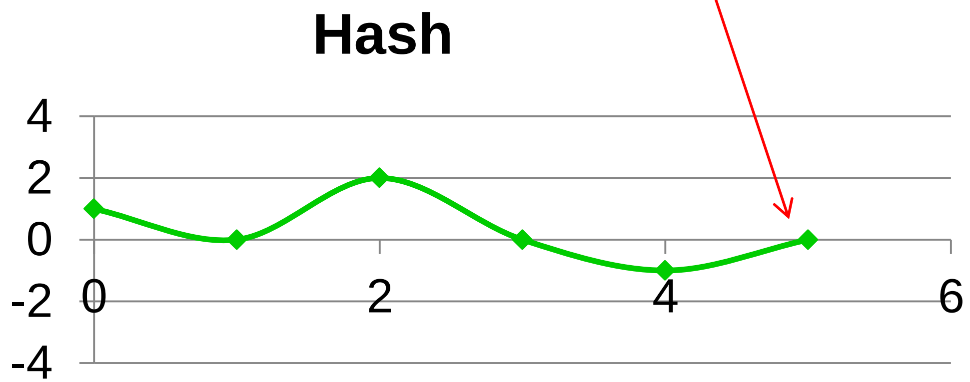

Content based Chunking

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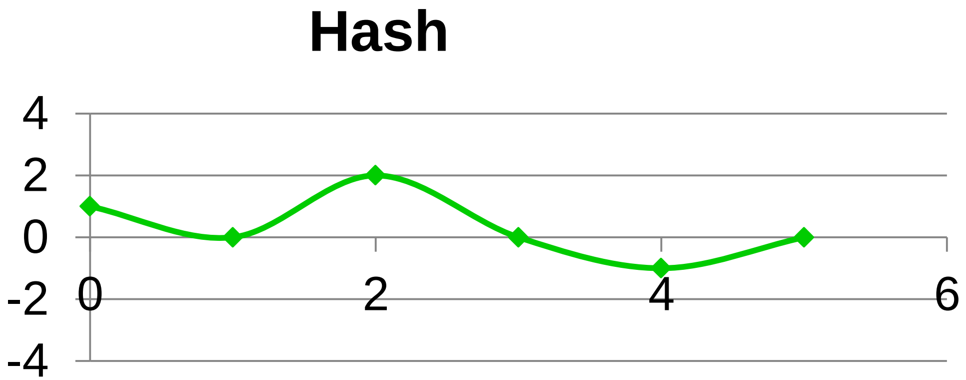
If Hash matches a particular pattern,

Declare a chunk boundary



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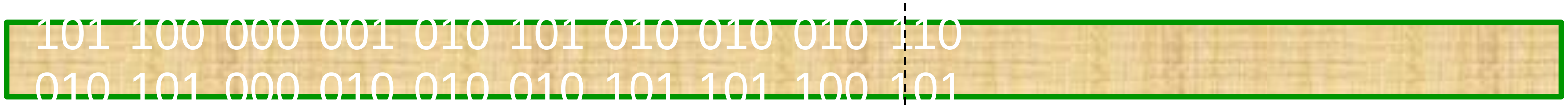

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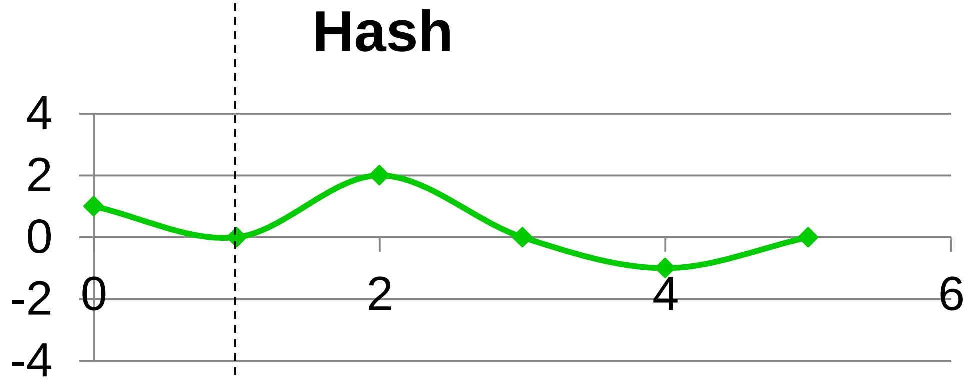

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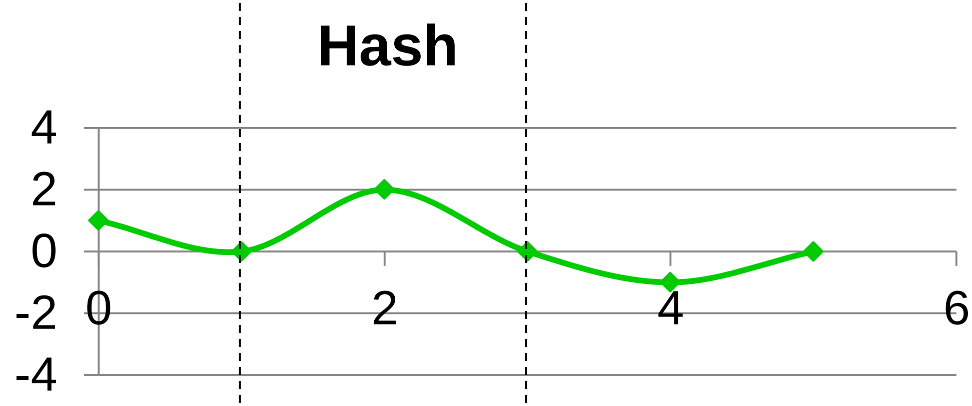

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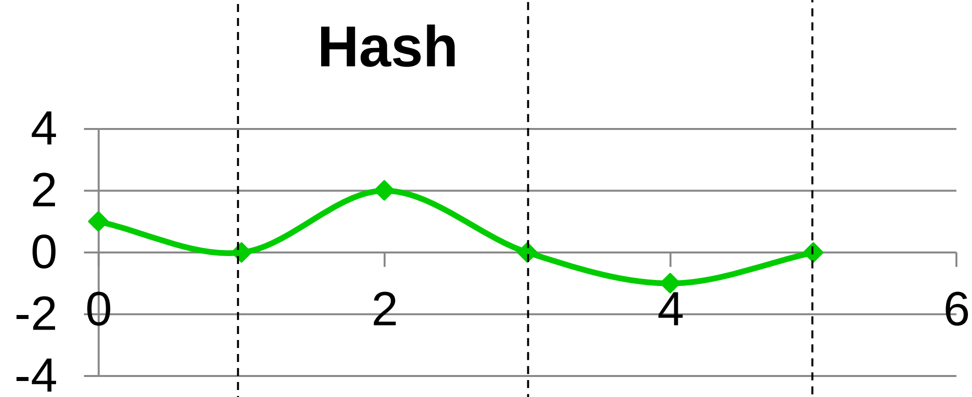

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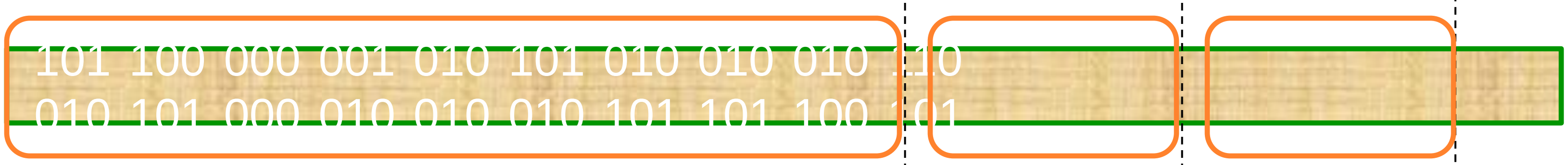
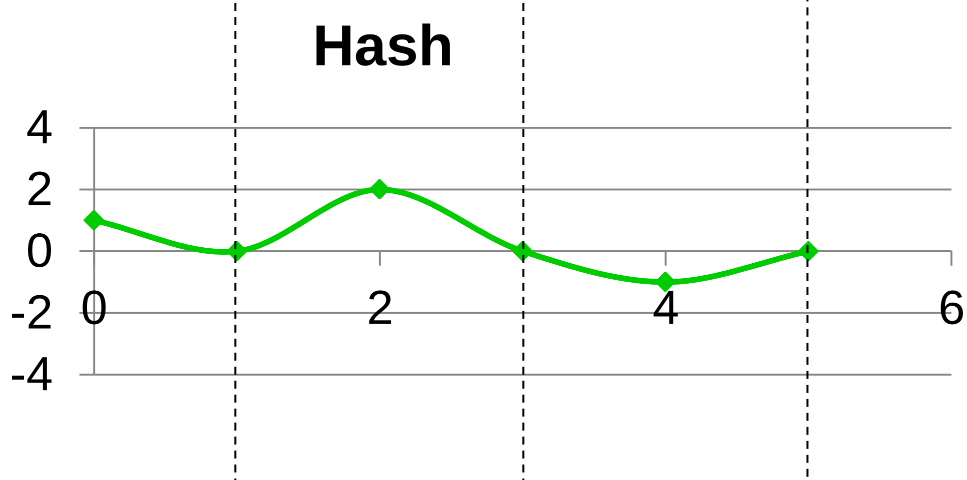


3 Chunks

If Hash matches a particular pattern,

Declare a chunk boundary

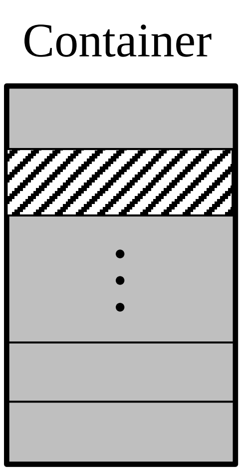


Index for Detecting Duplicate Chunks

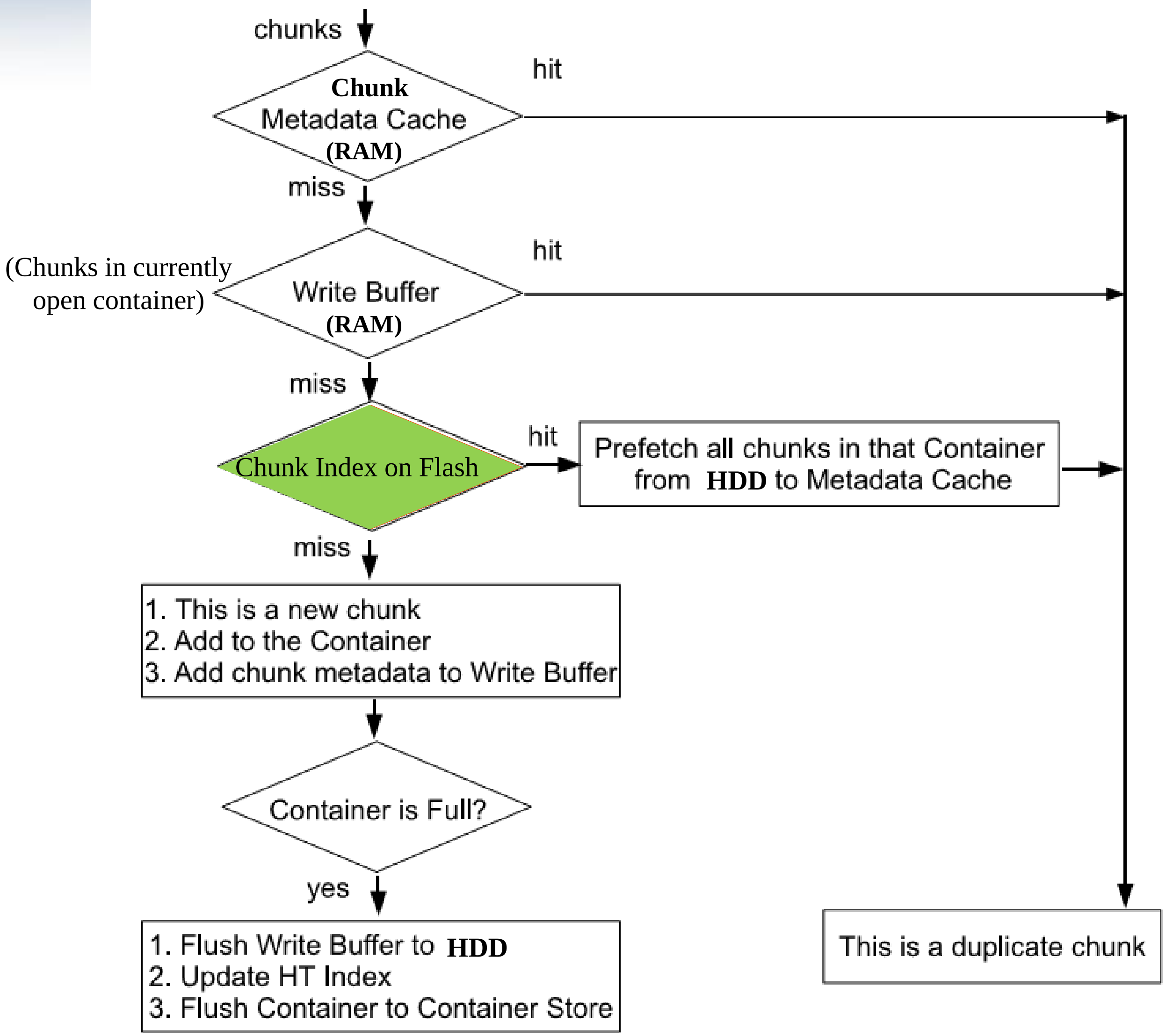
- Chunk hash index for identifying duplicate chunks
  - Key = 20-byte SHA-1 hash (or, 32-byte SHA-256)
  - Value = chunk metadata, e.g., length, location on disk
  - Key + Value ➔ 64 bytes
- Essential Operations
  - Lookup (Get)
  - Insert (Set)
- Need a high performance indexing scheme
  - Chunk metadata too big to fit in RAM
  - Disk IOPS is a bottleneck for disk-based index
  - Duplicate chunk detection bottlenecked by hard disk seek times (~10 msec)

Disk Bottleneck for Identifying Duplicate Chunks

- 20 TB of unique data, average 8 KB chunk size
  - 160 GB of storage for full index (2.5×10^9 unique chunks @64 bytes per chunk metadata)
- Not cost effective to keep all of this huge index in RAM
- Backup throughput limited by disk seek times for index lookups
  - 10ms seek time => 100 chunk lookups per second
    => 800 KB/sec backup throughput
  - No locality in the key space for chunk hash lookups
  - Prefetching into RAM index mappings for entire container to exploit sequential predictability of lookups during 2nd and subsequent full backups (Zhu et al., FAST 2008)



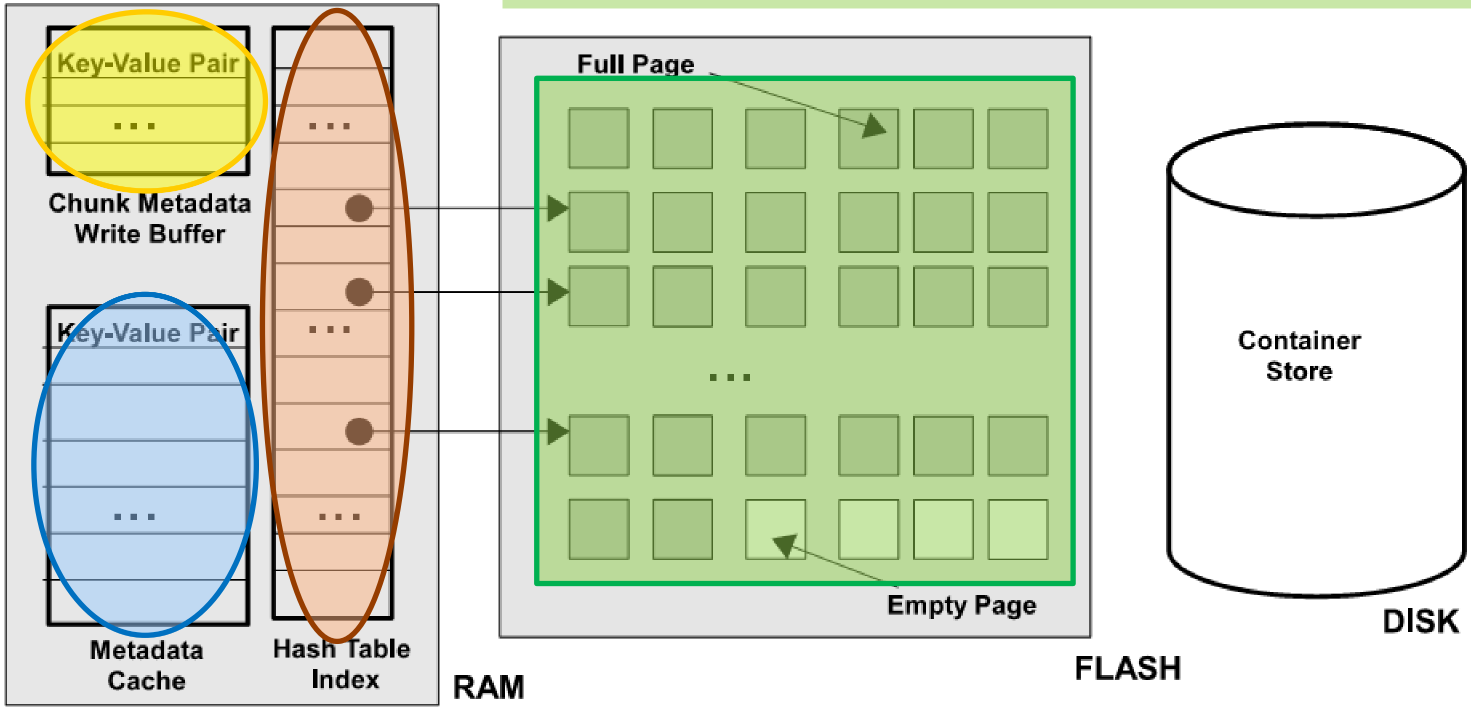
Storage Deduplication Process Schematic



ChunkStash: Chunk Metadata Store on Flash

RAM write buffer for chunk mappings in currently open container

Chunk metadata organized on flash in log-structured manner in groups of 1023 chunks => 64 KB logical page (@64-byte metadata/ chunk)



Prefetch cache for chunk metadata in RAM for sequential predictability of chunk lookups

Chunk metadata indexed in RAM using a specialized space efficient hash table

Performance Evaluation

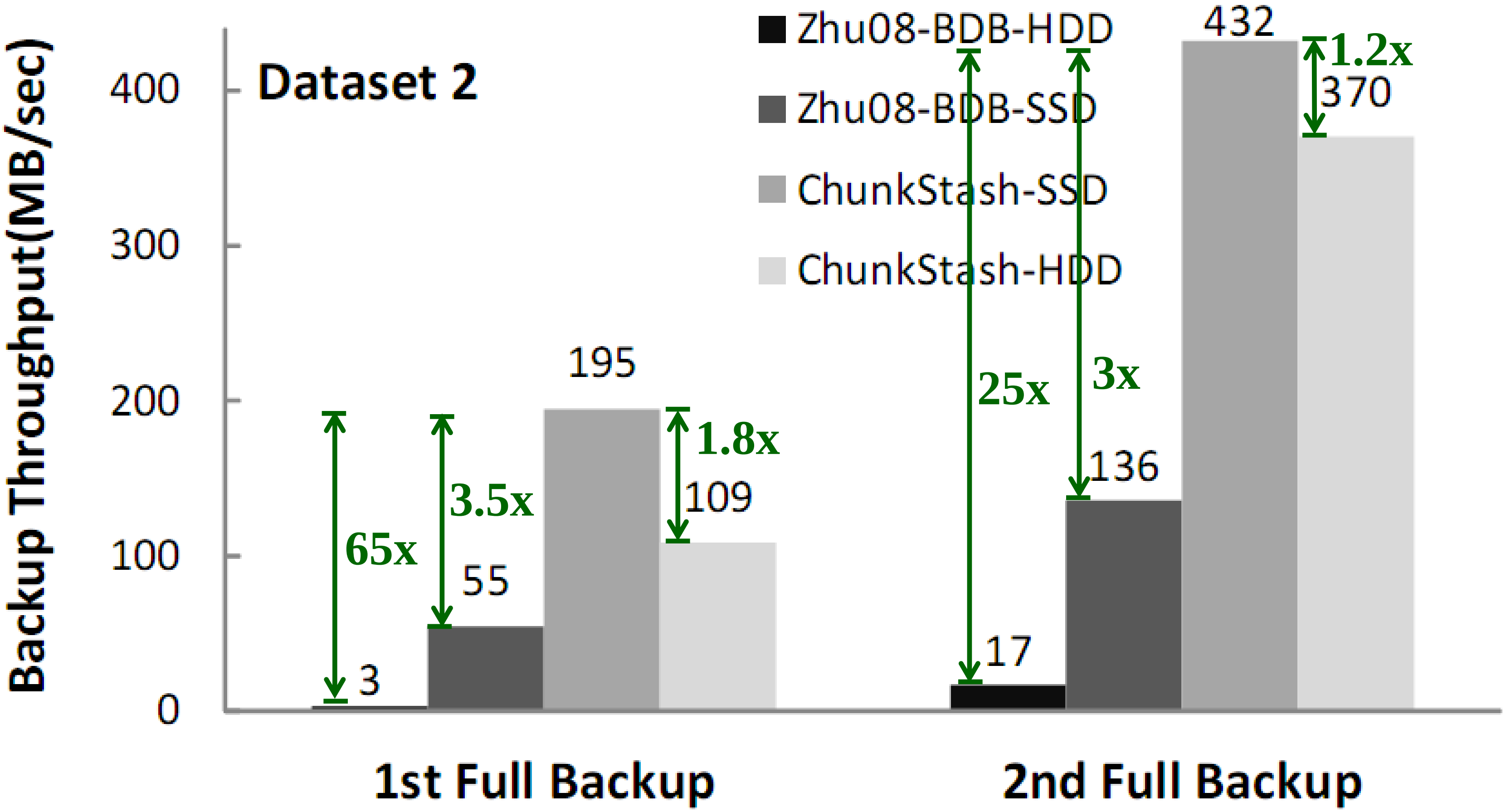
- Comparison with disk index based system
  - Disk based index (Zhu08-BDB-HDD)
  - SSD replacement (Zhu08-BDB-SSD)

  BerkeleyDB used as the index on HDD/SSD

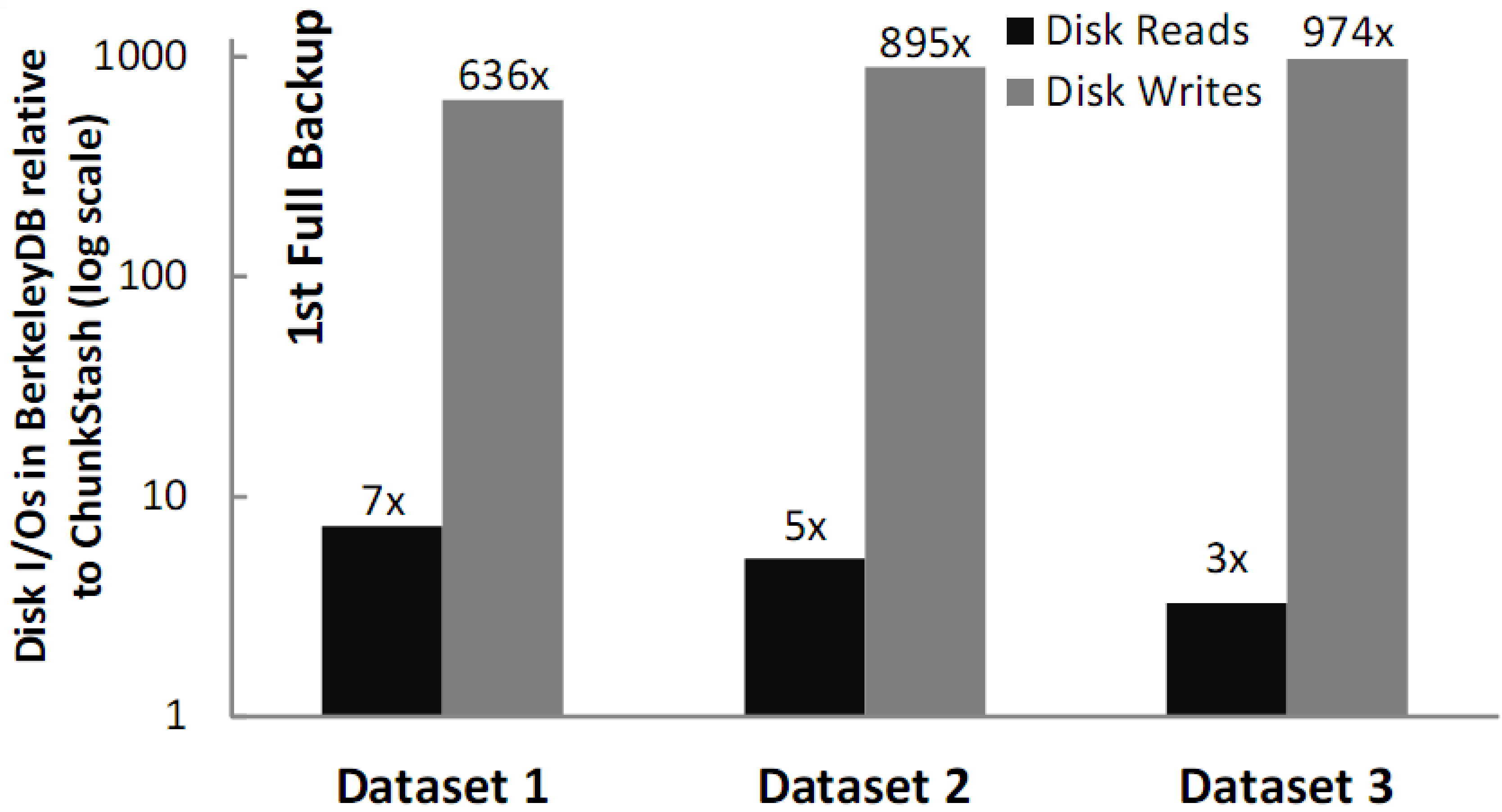
  - SSD replacement + ChunkStash (ChunkStash-SSD)
  - ChunkStash on hard disk (ChunkStash-HDD)
- Prefetching of chunk metadata in all systems
- Three datasets, 2 full backups for each

Trace	Size (GB)	Total Chunks	#Full Backups
Dataset 1	8GB	1.1 million	2
Dataset 2	32GB	4.1 million	2
Dataset 3	126GB	15.4 million	2

Performance Evaluation – Dataset 2



Performance Evaluation – Disk IOPS



Flash Memory Cost Considerations

- Chunks occupy an average of 4KB on hard disk
  - Store compressed chunks on hard disk
  - Typical compression ratio of 2:1
- Flash storage is 1/64-th of hard disk storage
  - 64-byte metadata on flash per 4KB occupied space on hard disk
- Flash investment is about 16% of hard disk cost
  - 1/64-th additional storage @10x/GB cost = 16% additional cost
- Performance/dollar improvement of 22x
  - 25x performance at 1.16x cost
- Further cost reduction by amortizing flash across datasets
  - Store chunk metadata on HDD and preload to flash

Summary

- System builders: Don’t just treat flash as disk replacement
  - Make the OS/application layer aware of flash
  - Exploit its benefits
  - Embrace its peculiarities and design around them
  - Identify applications that can exploit sweet spot between cost and performance
- Device vendors can help by exposing more APIs to the software layer for managing storage on flash
  - Can help to squeeze better performance out of flash with application knowledge
  - E.g., Trim(), newly proposed ptrim(), exists() from fusionIO

Thank You!

Email: {sudipta, jinl}@microsoft.com