The Bw-Tree Key-Value Store and Its Applications to Server/Cloud Data Management in Production

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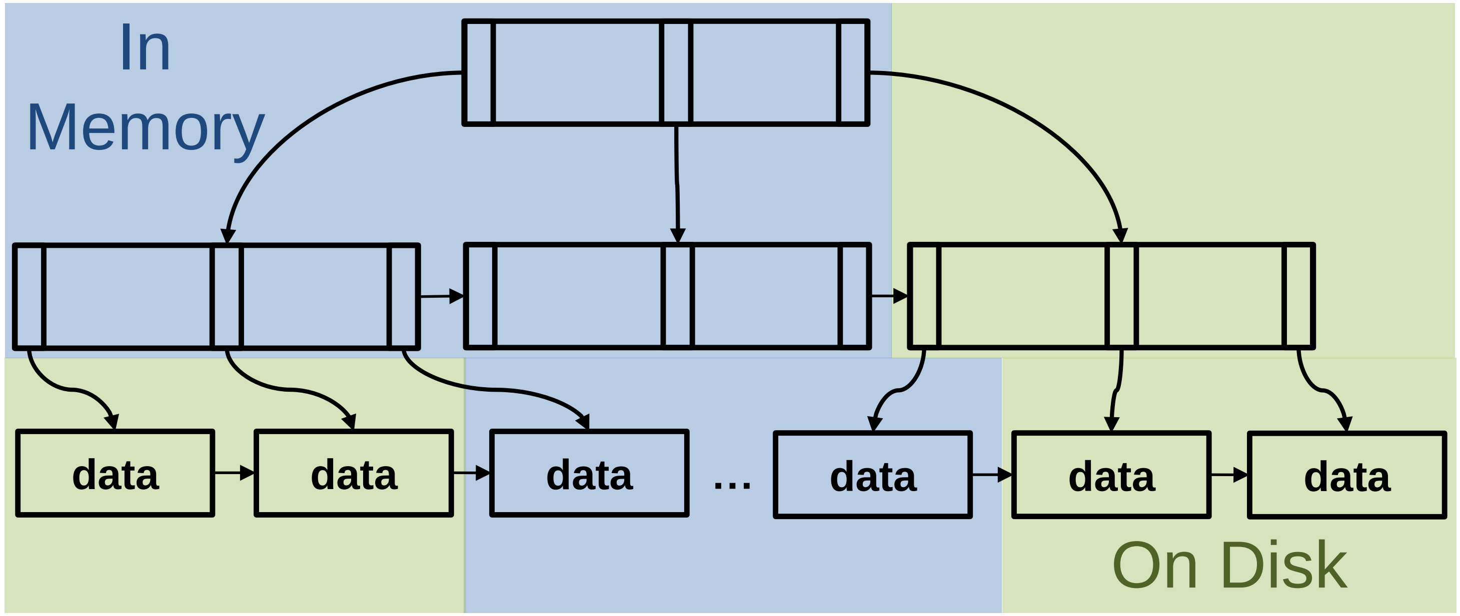
(Microsoft Research)

And Microsoft Product Group Partners across SQL Server, Azure DocumentDB, and Bing ObjectStore

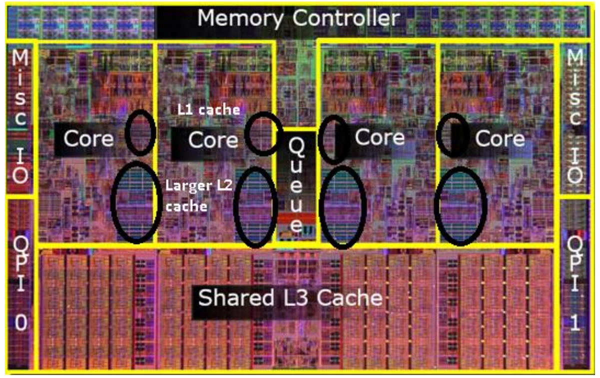
The B-Tree

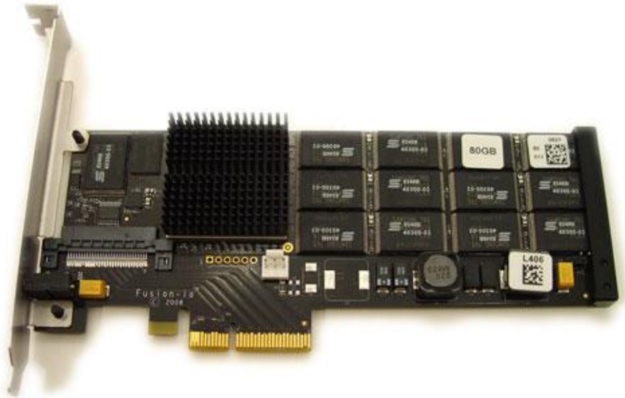
- Key-ordered access to records
- Separator keys in internal nodes (to guide search) and full records in leaf nodes
- Efficient point and range lookups
- Balanced tree via page split and merge mechanisms



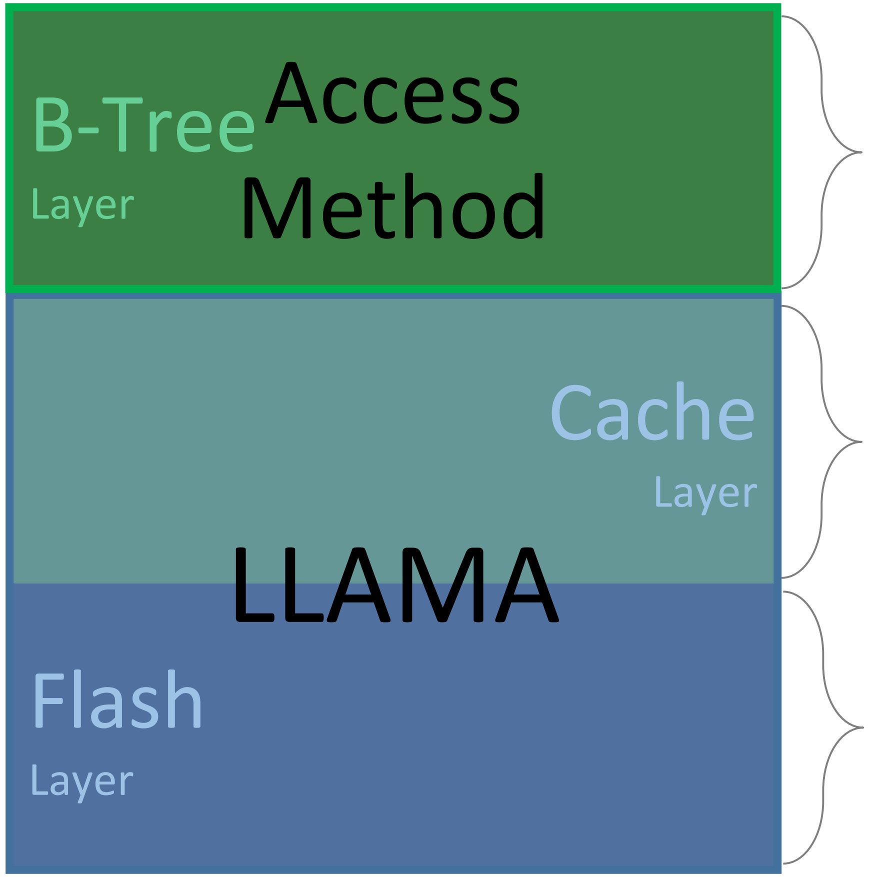
Design Tenets for A New B-Tree

- Lock-free operations for high concurrency
  - Exploit modern multi-core processors
- Log-structured Storage Organization
  - Exploit fast random read property of flash and work around inefficient random writes
- Delta updates to pages
  - Reduces cache invalidation in memory hierarchy
  - Reduces garbage creation and write amplification on flash, increases device lifetime





Bw-Tree Architecture



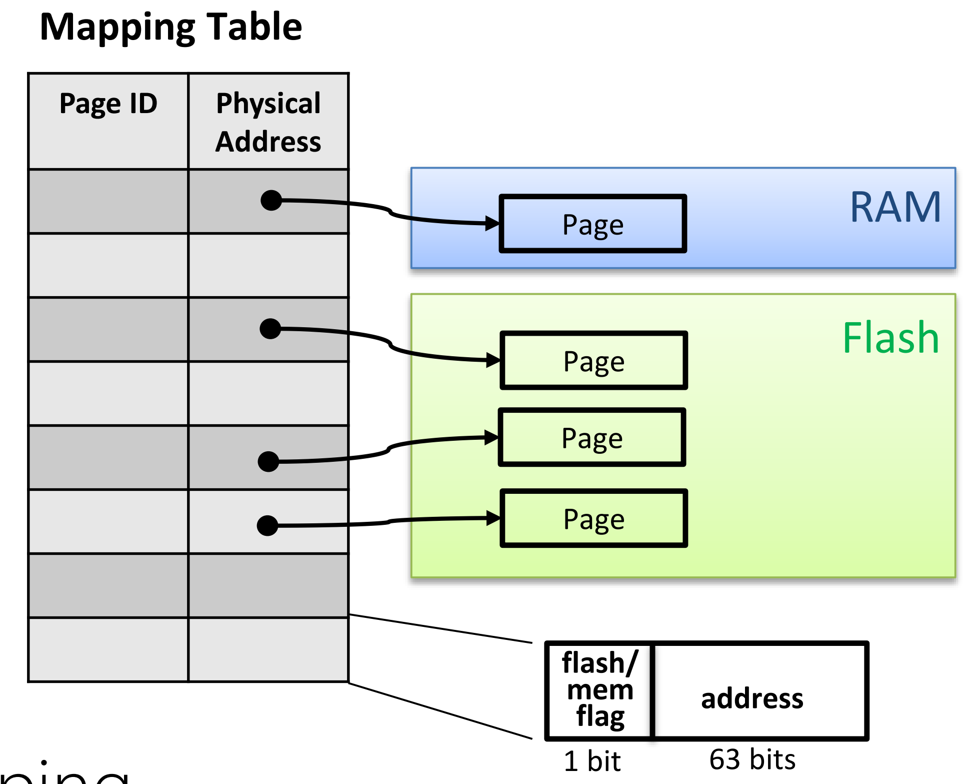
- Expose API
- B-tree search/update logic
- In-memory pages only

- Logical page abstraction for B-tree layer
- Moves pages between memory and flash as necessary

- Reads/Writes from/to storage
- Storage management

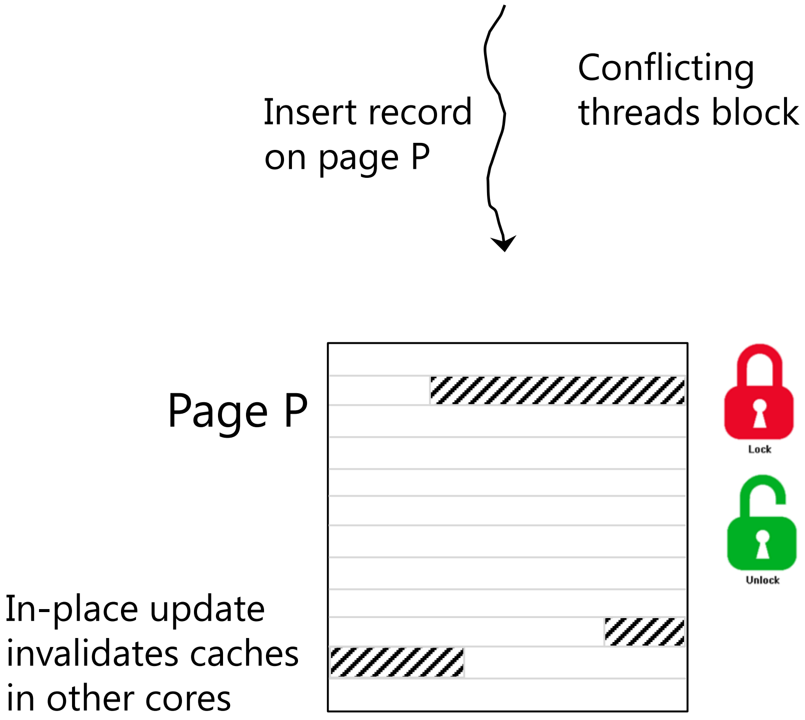
The Mapping Table

- Expose logical pages to the access method layer
  - Translates logical page ID to physical address
- Helps to isolate updates to a *single* page
- Central data structure for multi-threaded concurrency control
- Also used for log-structured store mapping
- Updated in lock-free manner [using compare-and-swap (CAS)]

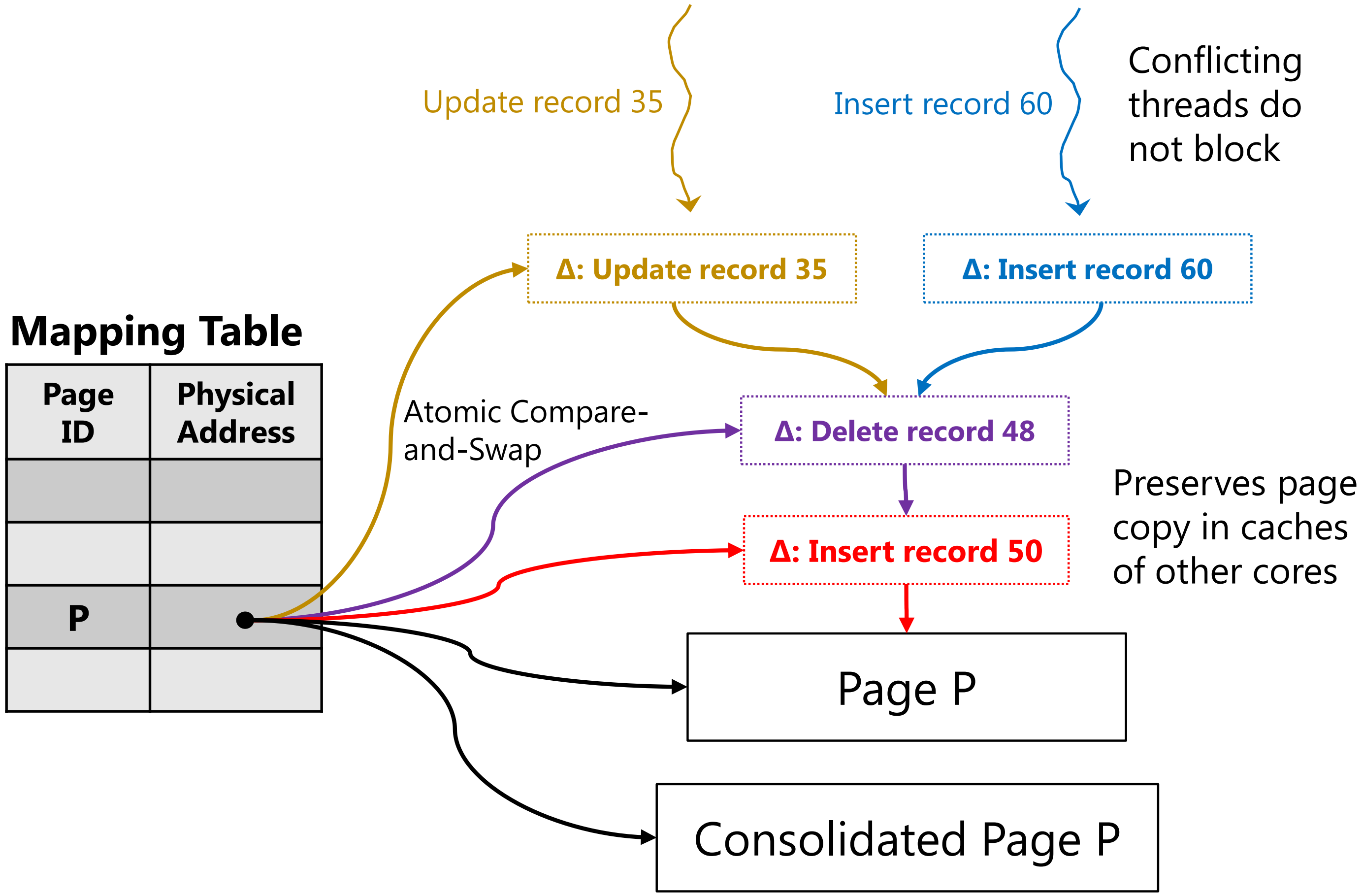


Highly Concurrent Page Updates with Bw-Tree

Classical B-Tree

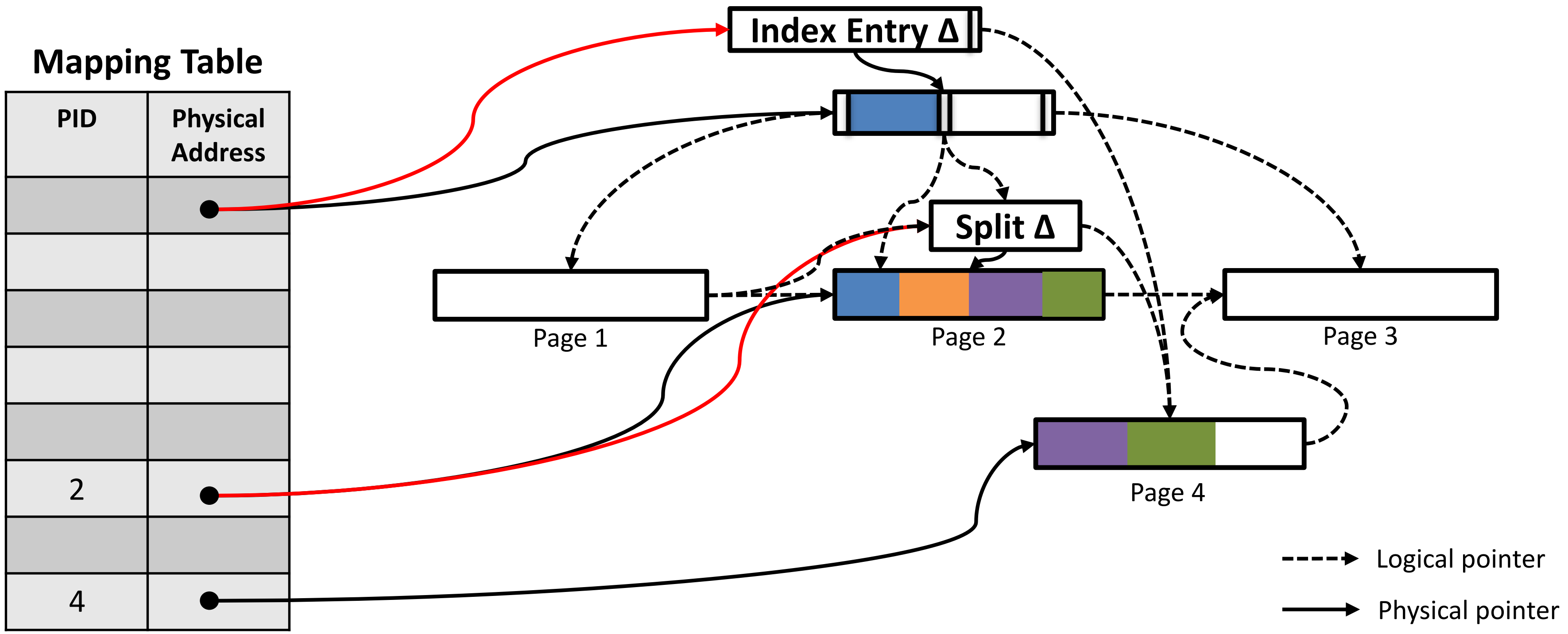


Bw-Tree



Bw-Tree Page Split

- No hard threshold for splitting unlike in classical B-Tree
  - Bw-Tree pages are elastic
- B-link structure allows "half-split" without locking
  - Install split at child level by creating new right page and linking left page to it
  - Install new separator key and pointer at parent level



Flash SSDs: Log-Structured Storage

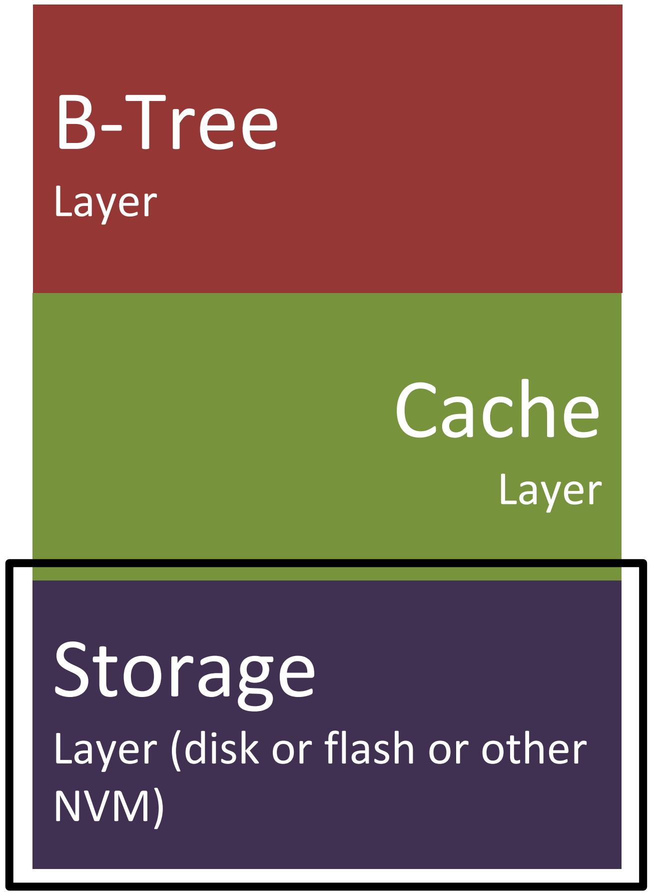
- Exploit benefits of flash and work around its quirks
  - Random reads are fast (10 – 100μsec)
  - Random writes (“in-place updates”) are expensive

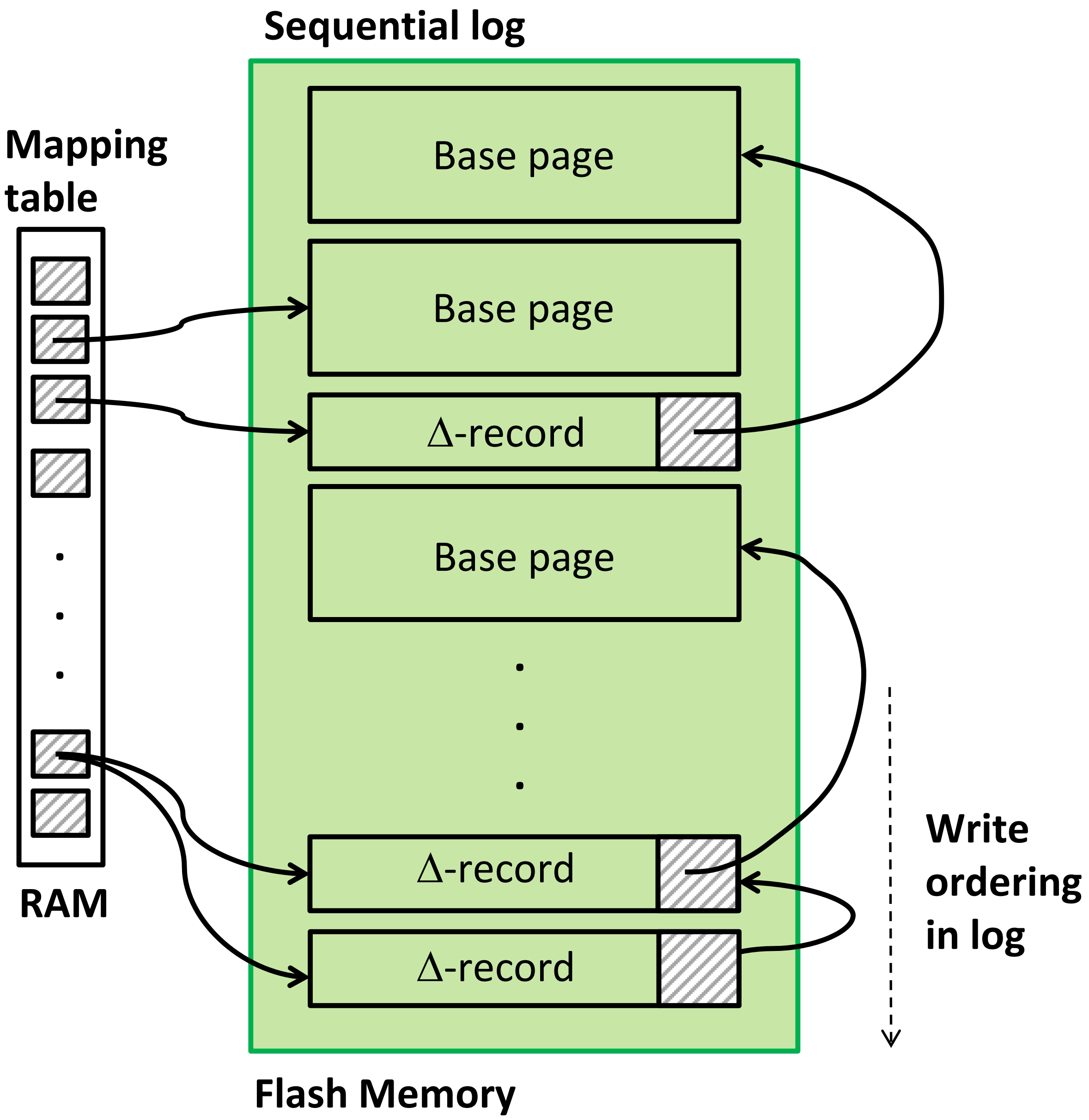
    -> Flash Translation Layer (FTL) cannot hide or abstract away device constraints
- Use flash in a log-structured manner

FusionIO 160GB ioDrive

LLAMA Log-Structured Store

- Suitable for flash + other benefits
- Amortize cost of writes over many page updates
  - Aggregate large amounts of new/changed data and append to the log in a single I/O
- Multiple random reads to fetch a "logical page"
  - Okay for flash, in the order of few tens of usec
- Works well for hard disks also
  - Benefit of amortizing page write cost
  - Random reads incur seek latency but mitigated by capturing working set of pages in RAM



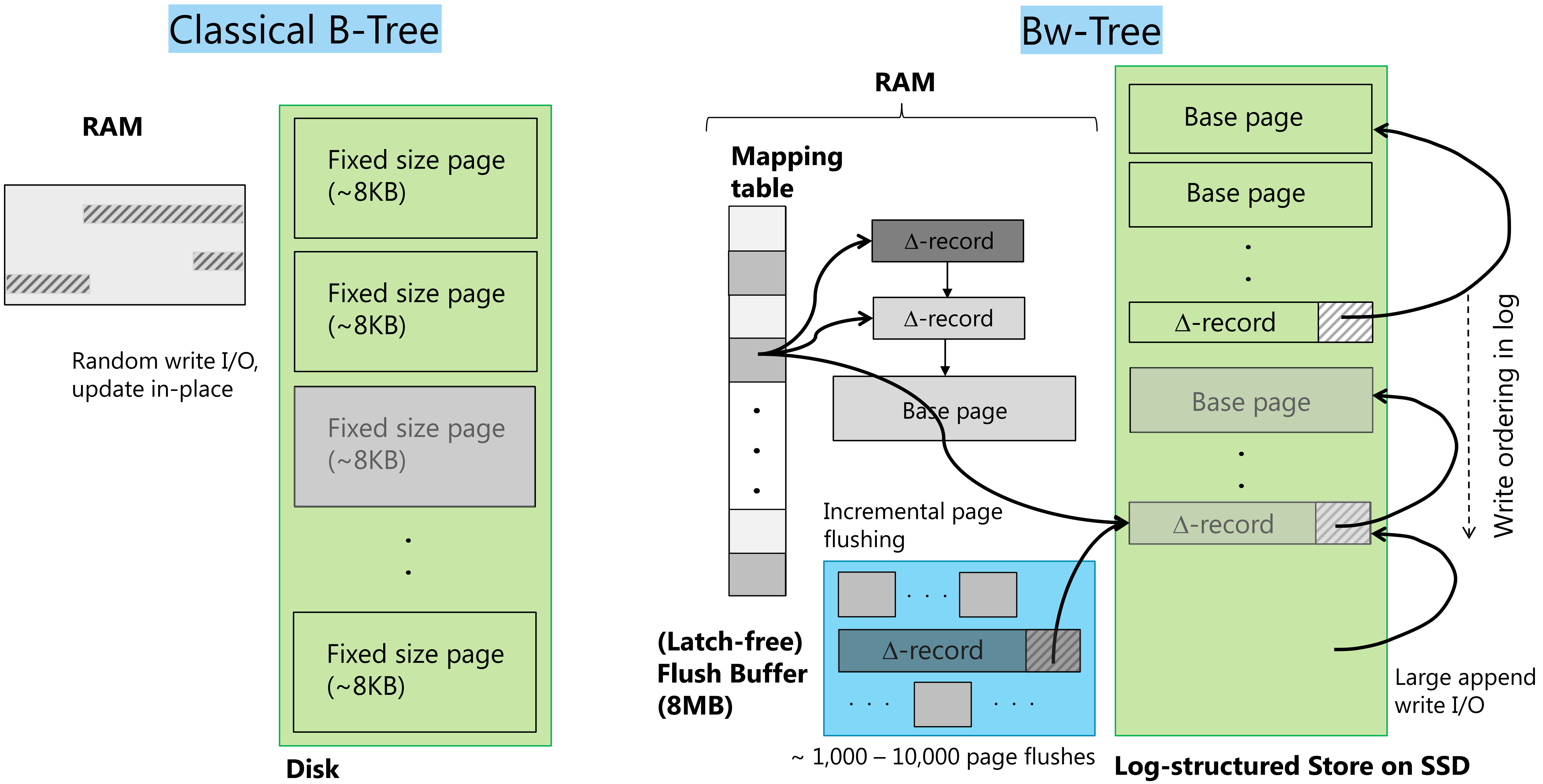


Sequential log
Mapping table
Base page
Base page
Δ-record
Base page
Δ-record
Δ-record
RAM
Write ordering in log
Flash Memory

Departure from Tradition: Page Layout on Flash

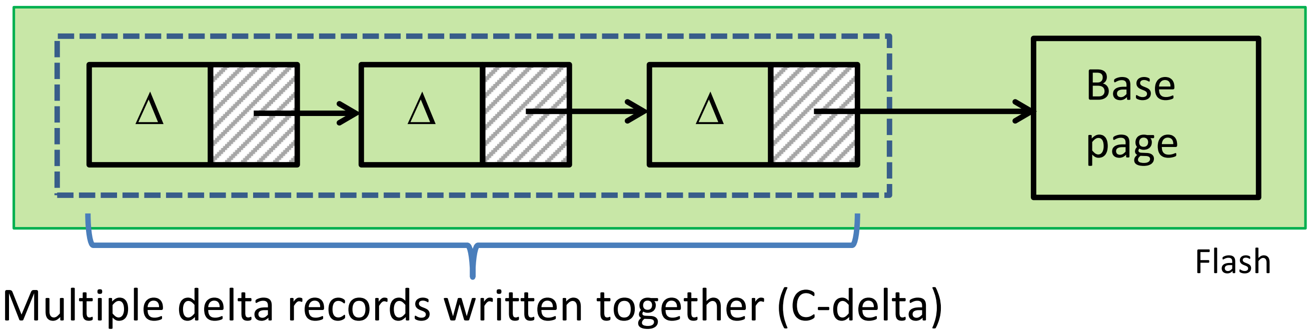
- Logical pages are formed by linking together records on possibly different physical pages
  - Logical pages do *not* correspond to whole physical pages on flash
  - Physical pages on flash contain records from multiple logical pages
- Exploits random access nature of flash media
  - No disk-like seek overhead in reading records in a logical page spread across multiple physical pages on flash
- Adapted from SkimpyStash (ACM SIGMOD 2011)

Write Optimized Storage Organization w/ Bw-Tree



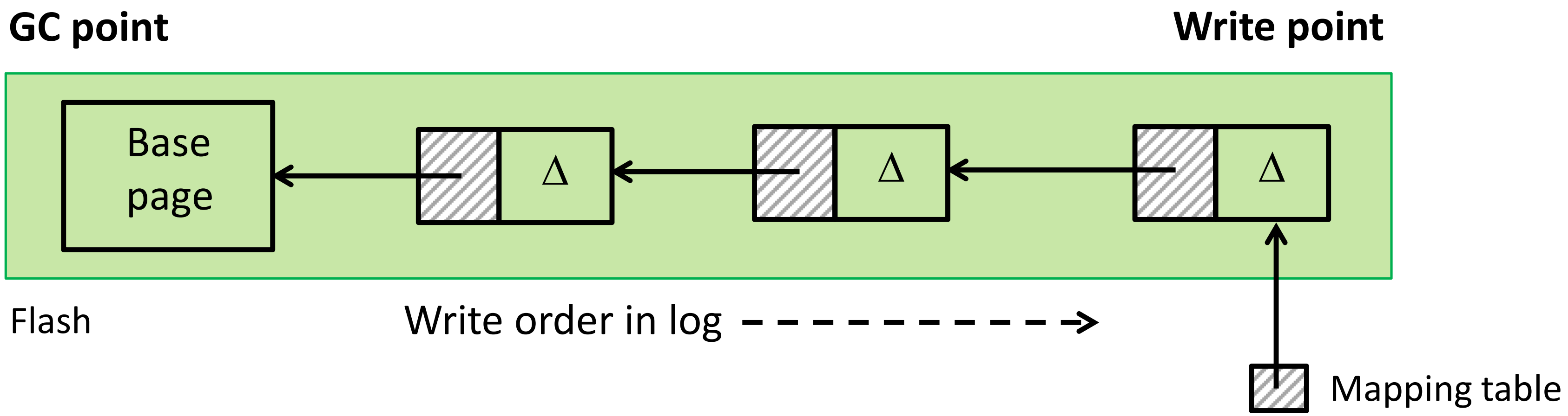
LLAMA: Optimizing Logical Page Reads

- Reading a “logical” page may involve reading delta records from multiple physical pages
  - Probably okay because of fast random access property of flash
  - Mitigated by capturing working set of pages in memory
- But we can reduce read I/Os further
  - Multiple delta records, when flushed together, are packed into a contiguous unit on flash (C-delta)
  - Pages consolidated periodically in memory also get consolidated on flash when they are flushed



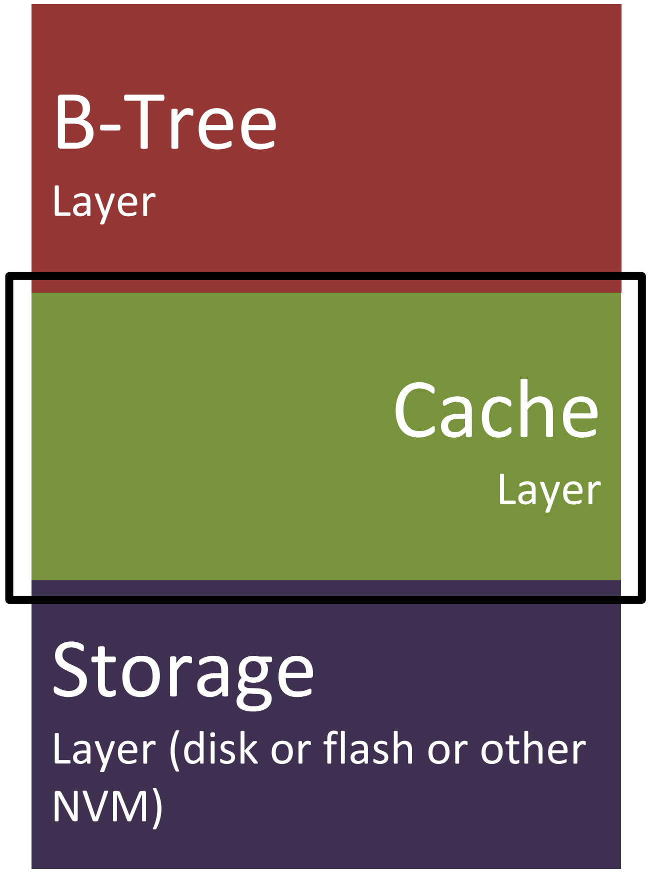
LLAMA: Garbage Collection on Flash

- Two types of record units in the log
  - Valid – Reachable from the flash offset in the mapping table
  - Orphaned – not reachable
- Garbage collection starts from oldest portion of log
  - Earliest written record (base page) on a “logical” page is encountered first
  - Avoid cascaded pointer updates up the chain => relocate entire logical page at a time, use this opportunity to consolidate



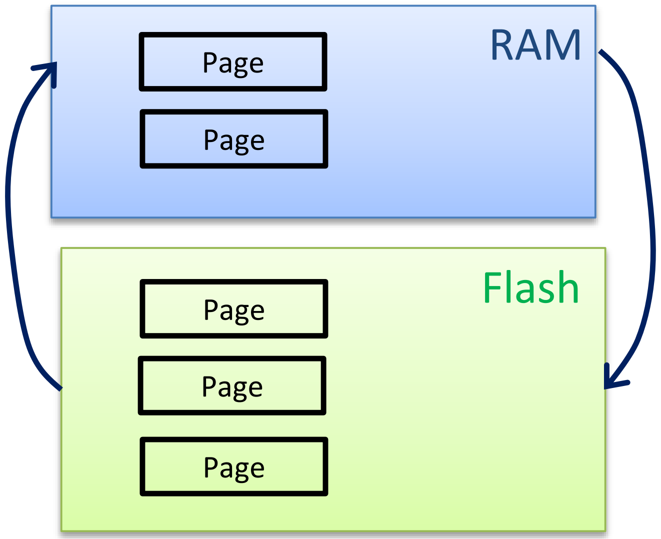
LLAMA: Cache Layer

- Provide abstraction of logical pages to access method layer
  - Mapping table containing RAM pointers or flash offsets
- Read pages into RAM from stable storage
- Flush pages to stable storage
  - Writes to flash ordered through flush buffers
- Swapout pages to reduce memory usage



LLAMA: Page Swapout

- Attempt to swapout pages when memory usage exceeds configurable threshold
- Uses variant of CLOCK algorithm
- Parallel page swapping functionality
  - Each accessor to Bw-Tree does small amount of page swapping work (“CLOCK sweep”) if needed
- RAM pointer replaced by flash offset in mapping table
- Page structure deallocated using epoch based memory garbage collection

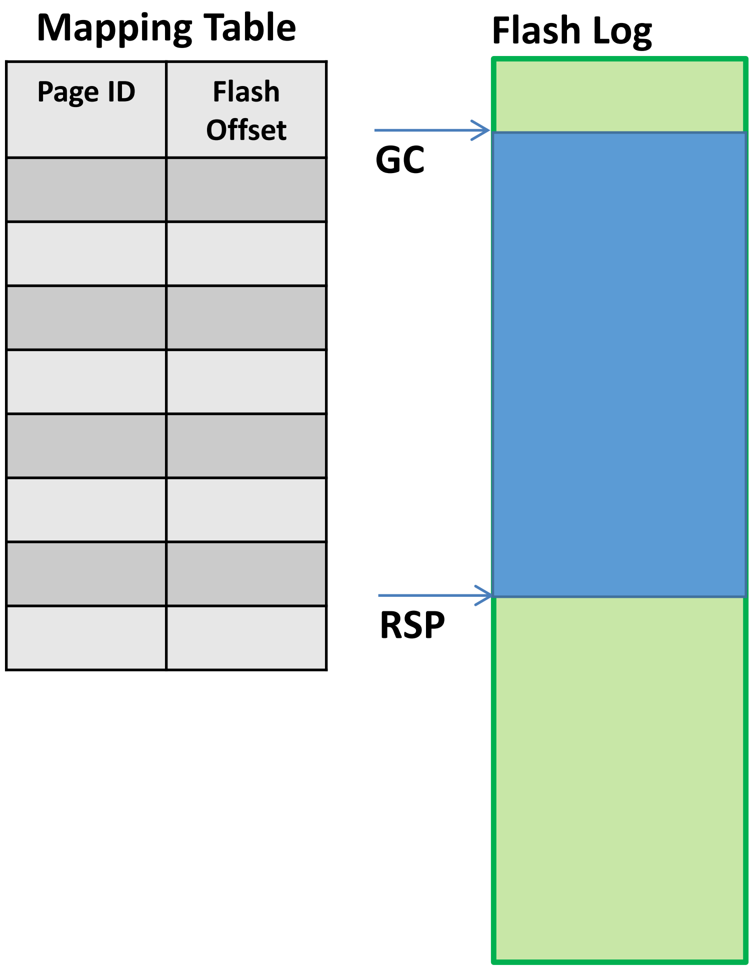


Bw-Tree/LLAMA Checkpointing

- B-Tree layer checkpointing (for durability)
  - Flush pages to flush buffer and subsequently to storage
- LLAMA checkpointing (for fast recovery)
  - Write the mapping table to flash

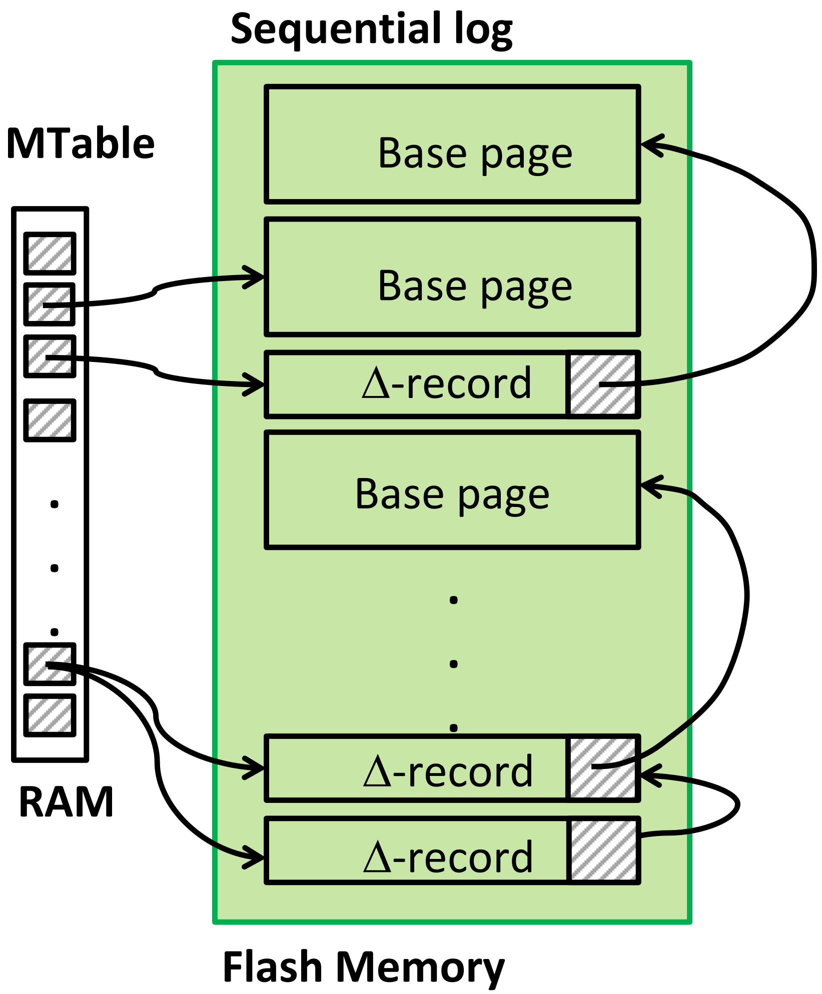
    -> When an entry contains RAM address, obtain flash address from the in-memory page

    -> Unused entries are written as zeroes
  - Record write position in log when the checkpoint started
  - Alternate between two fixed regions on flash for each checkpoint

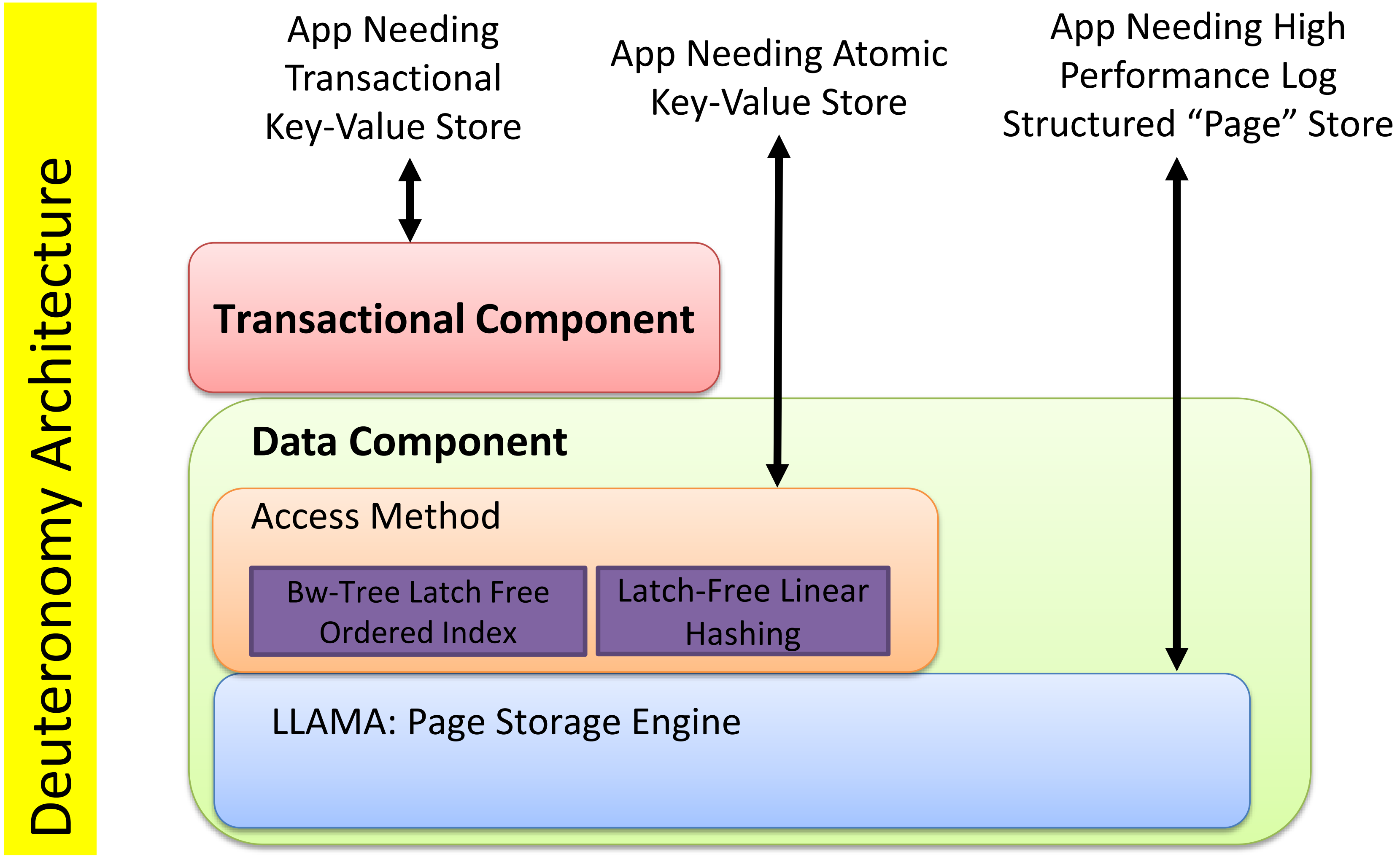


Bw-Tree Fast Recovery

- Restore mapping table from latest checkpoint region
- Scan from log position recorded in checkpoint to end of log
  - Read page ID from C-delta on log and update flash offset in mapping table
- Restore Bw-tree root page LPID
- Optimizations for fast cache warm-up

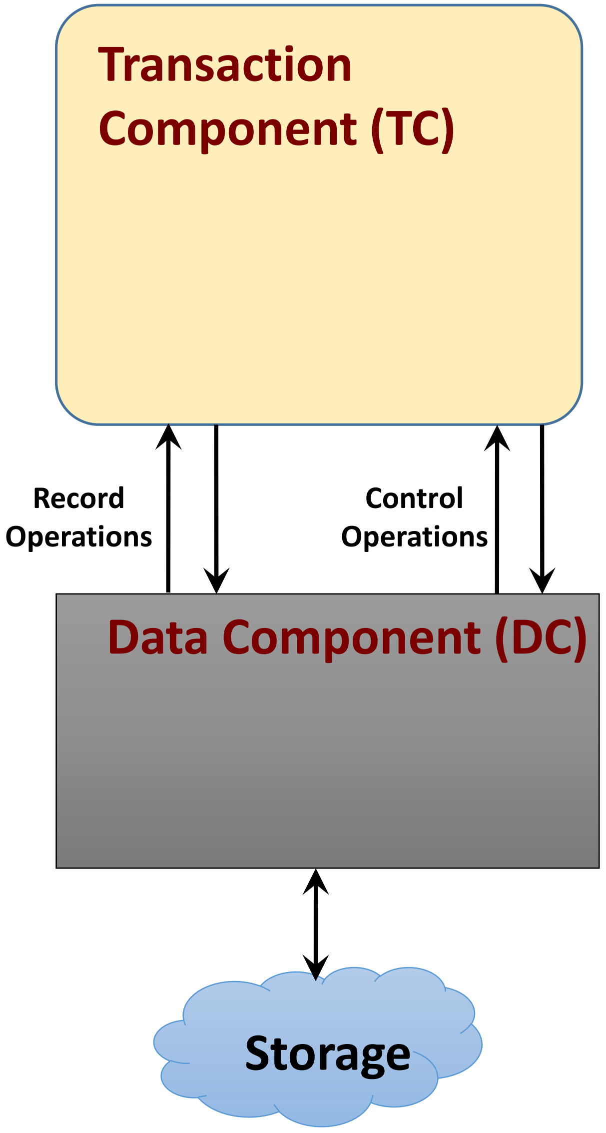


Bw-Tree: Support for Transactions



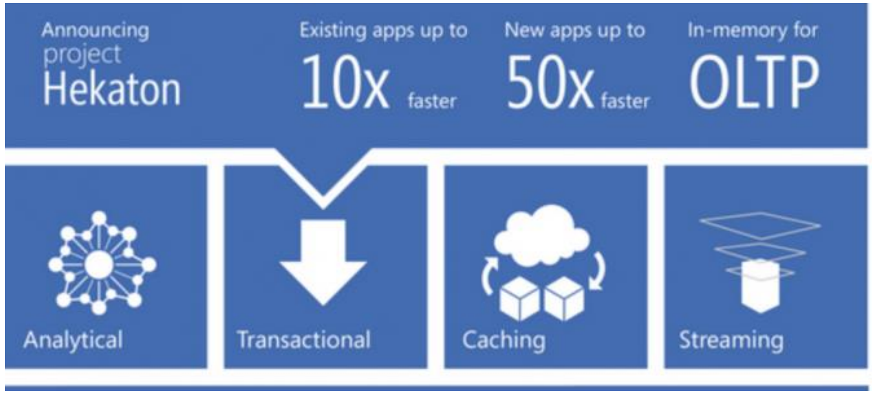
End-to-end Crash Recovery

- Data Component (DC) recovery
  - Bw-Tree fast recovery as described
- Transactional Component (TC) recovery
  - Helps to recover unflushed data at DC “up to” end of stable log (WAL) at time of crash
  - Requires DC to recover to a logically consistent state first

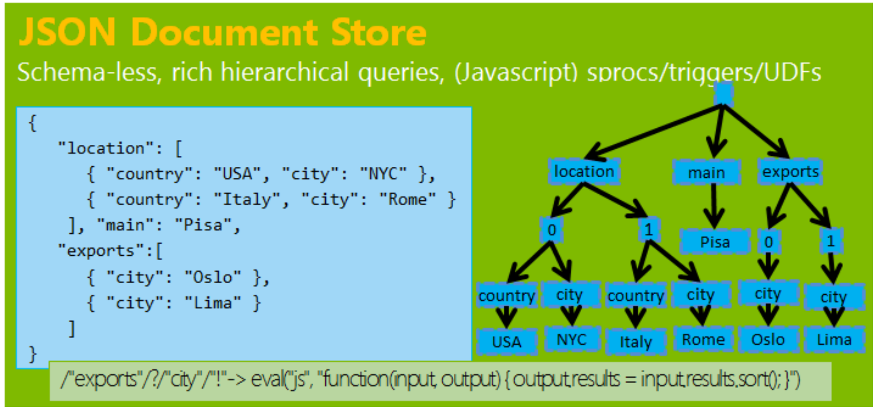


Bw-Tree in Production

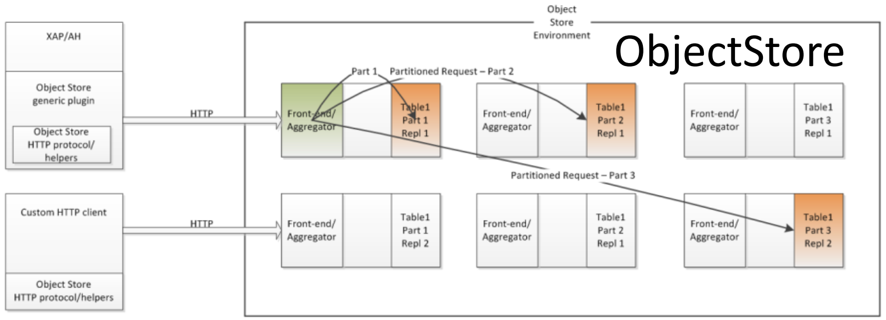
- Key-sequential index in SQL Server Hekaton
  - Lock-free for high concurrency, consistent with Hekaton's overall non-blocking main memory architecture



- Indexing engine in Azure DocumentDB
  - Rich query processing over a schema-free JSON model, with *automatic indexing*
  - Sustained document ingestion at high rates



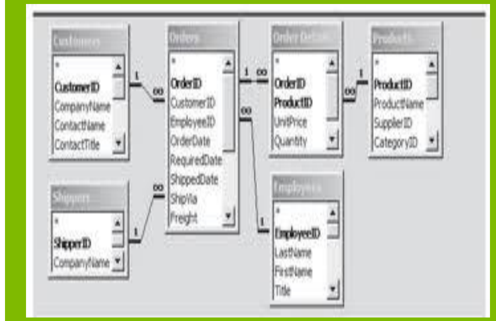
- Sorted key-value store in Bing ObjectStore
  - Support range queries
  - Optimized for flash SSDs



DocumentDB

Relational Stores

Fully schematized, relational queries, transactions (e.g., SQL Azure, Amazon RDS, SQL IaaS)



Key-Value/ Column Family Stores

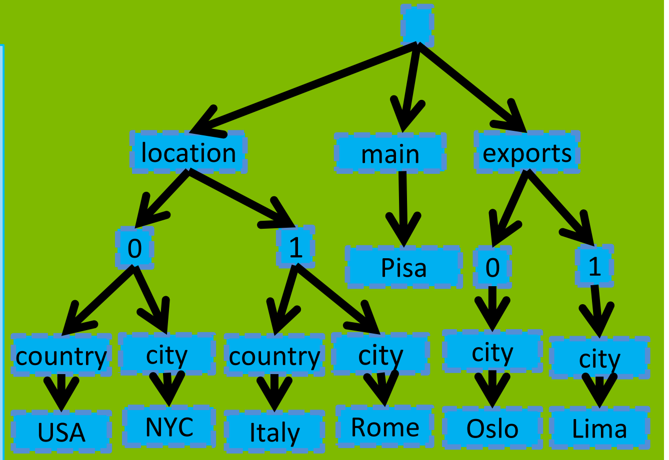
Schema-less with opaque values, lookups on keys (e.g., Azure Tables, HBASE, BigTable, LevelDB, Cassandra, …)

Key	Value
k1	XML
k2	.NET
k3	Java

(JSON) Document Stores

Schema-less, rich hierarchical queries, (Javascript) sprocs/triggers/UDFs (e.g. MongoDB, CouchDB, Espresso, …)

```
{
   "location": [
      { "country": "USA", "city": "NYC" },
      { "country": "Italy", "city": "Rome" }
    ], "main": "Pisa",
   "exports":[
      { "city": "Oslo" },
      { "city": "Lima" }
    ]
}
```




```
/"exports"/?/"city"/"!"-> eval("js", "function(input, output) { output.results = input.results.sort(); }")
```

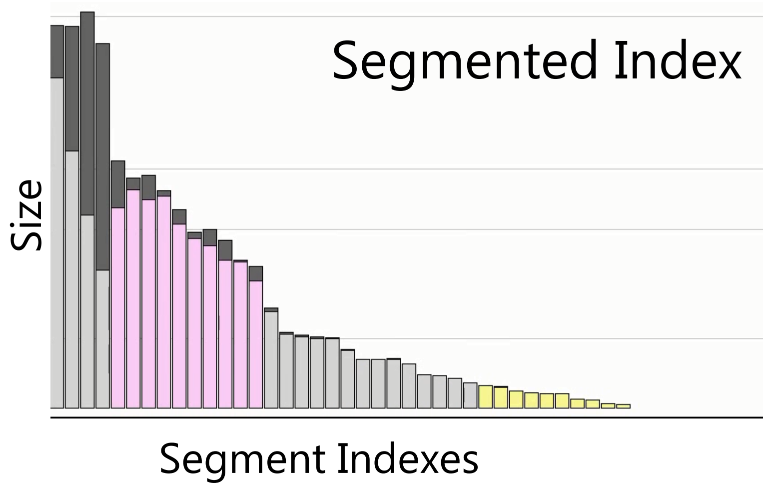
DocumentDB: Differentiated Feature set

- Formal query model optimized for queries over schema-less documents at scale
  - Support for relational and hierarchical projections
- Consistent indexing in face of rapid, sustained high volume writes (optimized for flash SSDs)
- Developer tunable consistency-availability tradeoffs with SLAs
- Low latency, (Javascript) language integrated, transactional CRUD on storage partitions
- Elastic scale, resource governed, multi-tenant PaaS

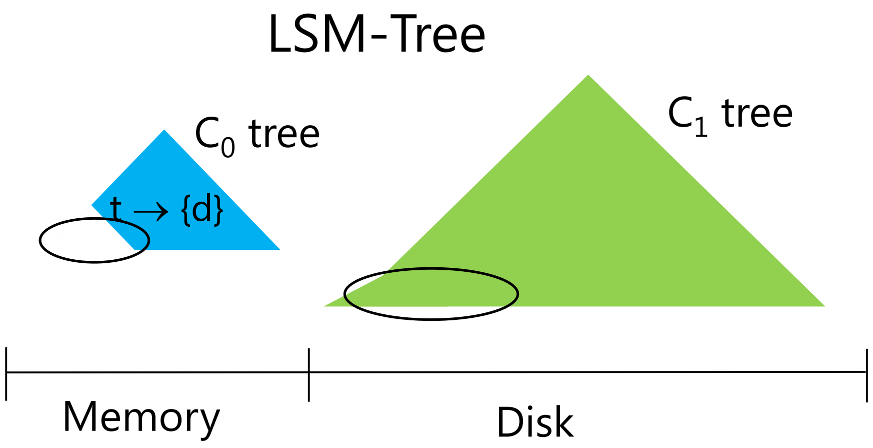
In Search for the ~~Right~~ Write Index

Consistent Indexing over schema-less documents is an overly constrained design space

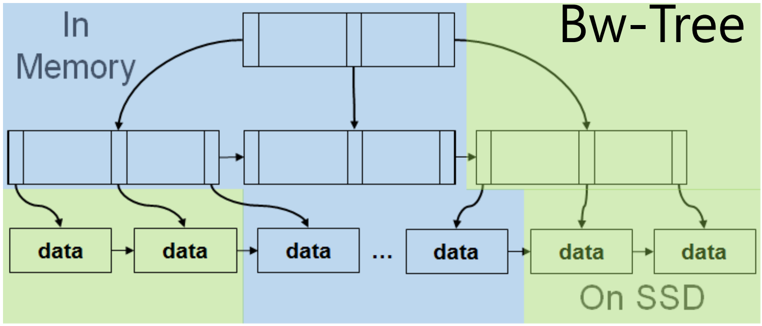
- Sustained high volume writes <u>without</u> any term locality
- Queries should honor various consistency levels
- Extremely high concurrency
- Multi-tenancy with strict, reservation based, sub-process level resource governance



- Segment indexes written one by one as documents arrive
- Queries need to scan multiple segments, hence **tradeoff between query time and freshness**
- Background merge job => leads to **high write amplification** (> 10x).



- Insertions batched in C0 to reduce write I/Os
- Periodic **bulk merge** of key ranges in C0 with those in C1 and made durable to C1
- **No semantic value merge** support
- **Read I/O before write** => **Slows down insertions**



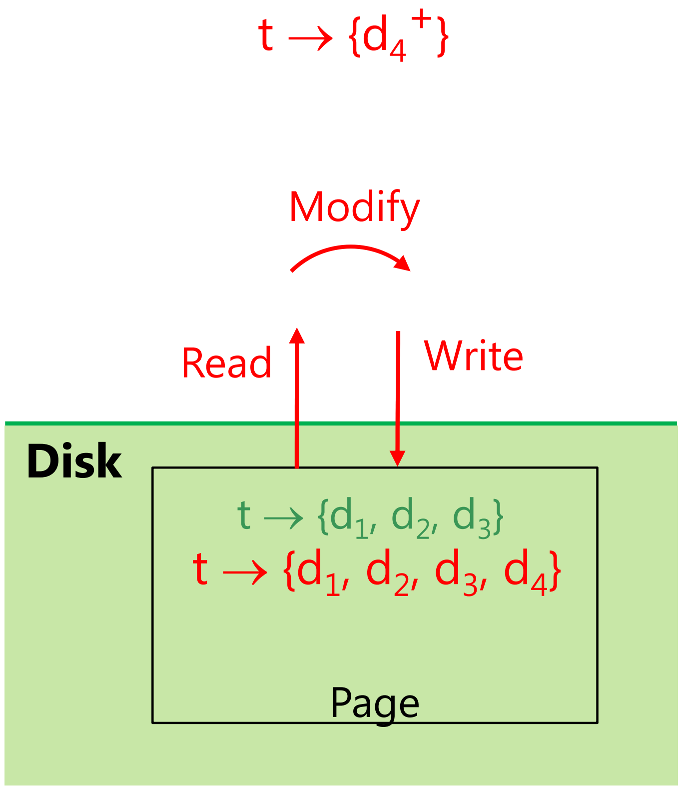
- Highly concurrent: **latch-free**
- **Incremental durability via batch writes**, but no large merges
- Blind incremental updates: **avoid read-before-write**
- **Consistent indexing** in face of **sustained document ingestion**
- **Optimized for SSD** (works well for HDD)
- Flexible **resource governance**

Efficient Index Updates with Bw-Tree

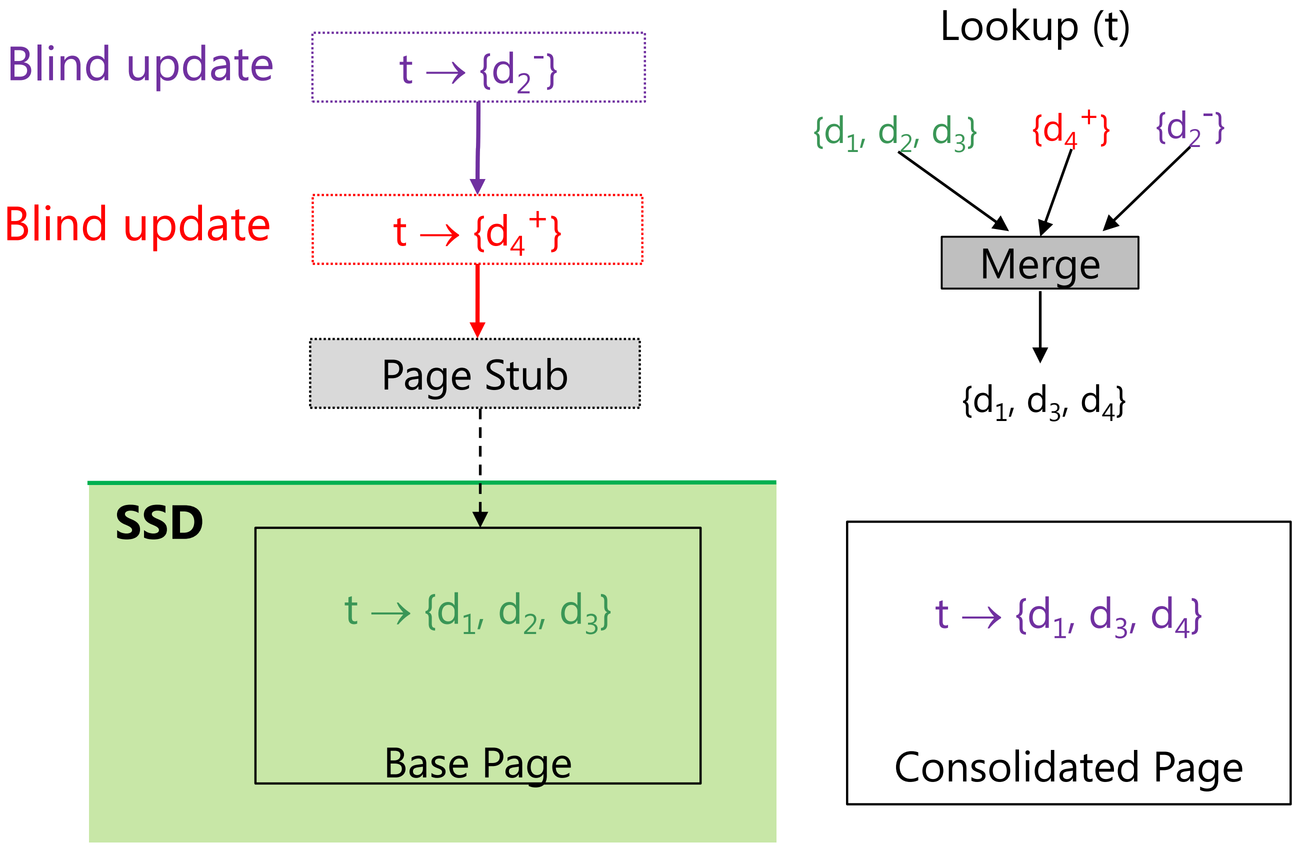
Key Challenges

- Index update: No key locality; cannot afford a Read to do the Write; low Write Amplification
- Queries: Low Read Amplification
- Frugal resource budget

Classical B-Tree

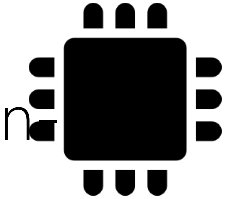


Bw-Tree



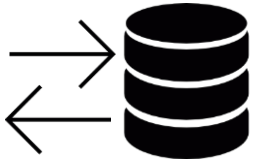
Bw-Tree Resource Governance

- CPU resource governance
  - Threads calling into Bw-Tree do not block (upon I/O or memory page access)
  - Top-level scheduler controls thread budget per replica



- Memory resource governance
  - Dynamically configurable buffer pool limit

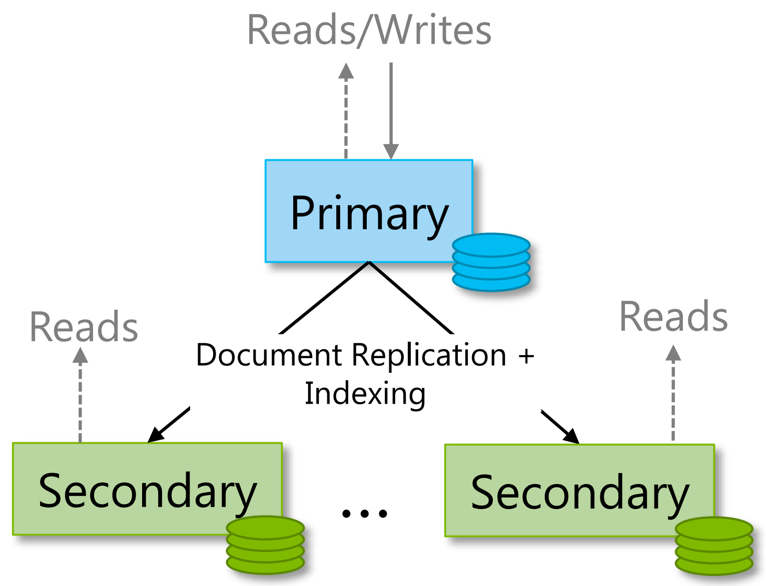
- IOPS resource governance
  - Check resource usage before issuing I/O, retry after dynamically computed timeout interval

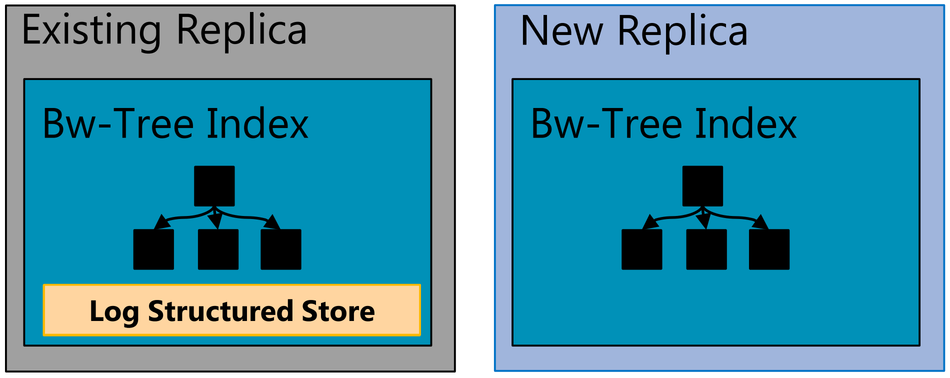


- Storage resource governance
  - LLAMA log-structured store can grow/shrink dynamically
  - Self-adjusting based on logical data size

Bringing up Bw-Tree Replica

- Obtain Bw-Tree physical state stream from primary
  - LLAMA checkpoint file (most recent)
  - Valid portion of LLAMA log (between GC and write points)
- Bring up Bw-Tree using fast recovery
- Catch up with primary
  - Replay logical operations from primary with LSNs upward of last (contiguous) LSN in recovered Bw-Tree





Bw-Tree: Summary

- Classical B-Tree redesigned from ground up for modern hardware and cloud
  - Lock-free for high concurrency on multi-core processors
  - Delta updating of pages in memory for cache efficiency
  - Log-structured storage organization for flash SSDs
  - Flexible resource governance in multi-tenant setting
  - Transactional component can be layered above as part of Deuteronomy architecture
- Shipping in Microsoft's server/cloud offerings
  - Key-sequential index in SQL Server Hekaton
  - Indexing engine in Azure DocumentDB
  - Sorted key-value store in Bing ObjectStore
- Going forward
  - Layer a transactional component on top as per Deuteronomy architecture (CIDR 2015, VLDB 2016)
  - Open-source the codebase