L-Store: Lineage-based Storage Architectures

ECS165A: Winter 2024

Slides are adopted from Sadoghi, et al.

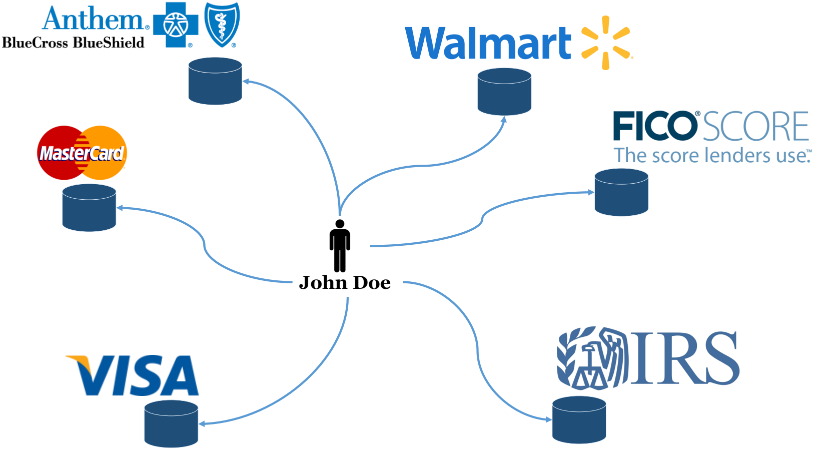
L-Store: A Real-time OLTP and OLAP System, EDBT'18

ExpoLab Creativity Unfolded

UC DAVIS UNIVERSITY OF CALIFORNIA

ResilientDB Security, Privacy Reloaded

Data Management at Macroscale: The Four V's of Big Data



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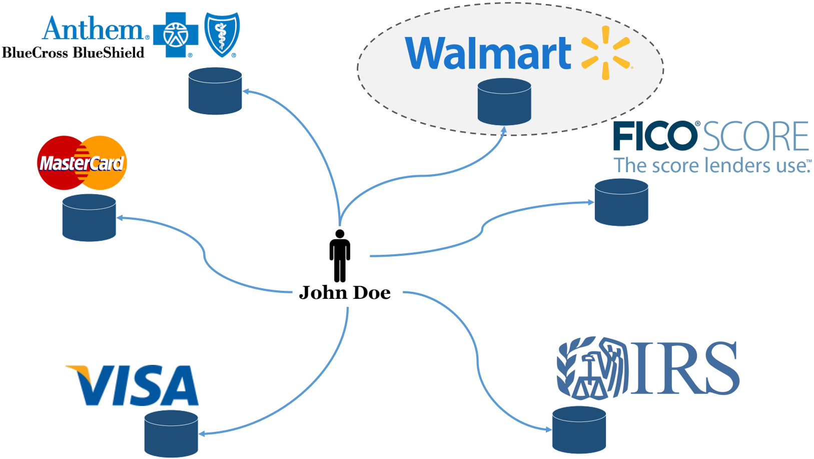
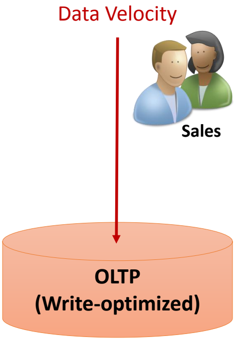


Data Management at Microscale: Volume & Velocity



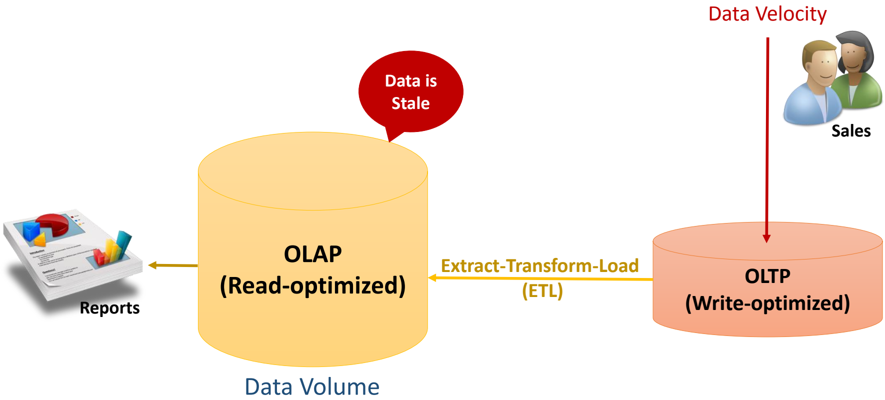
Data Velocity

Sales

OLTP
(Write-optimized)

Walmart

Data Management at Microscale: Volume & Velocity



Data Velocity

Sales

Data is Stale

OLAP (Read-optimized)

Extract-Transform-Load (ETL)

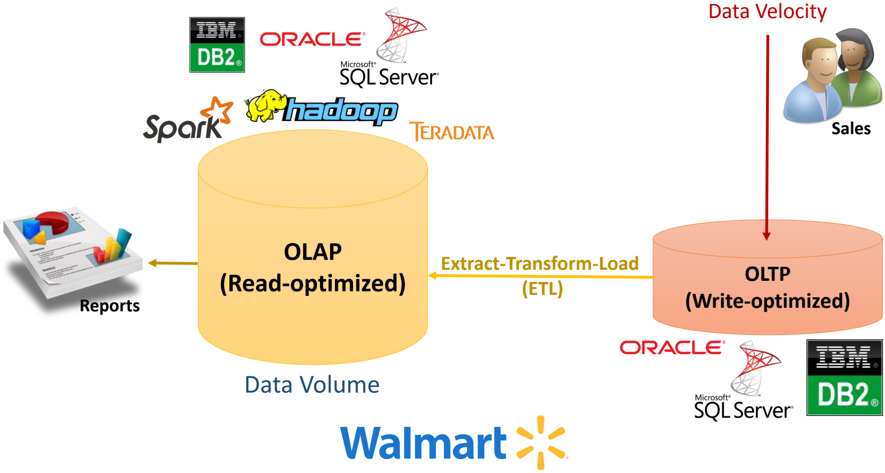
OLTP (Write-optimized)

Reports

Data Volume

Walmart

Data Management at Microscale: Volume & Velocity



Data Velocity

Sales

OLTP
(Write-optimized)

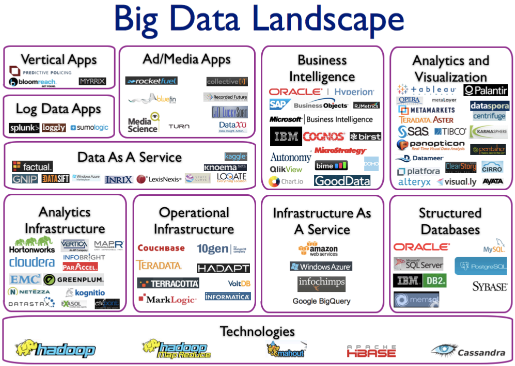
Extract-Transform-Load
(ETL)

OLAP
(Read-optimized)

Reports

Data Volume

One Size Does not Fit All As of 2012



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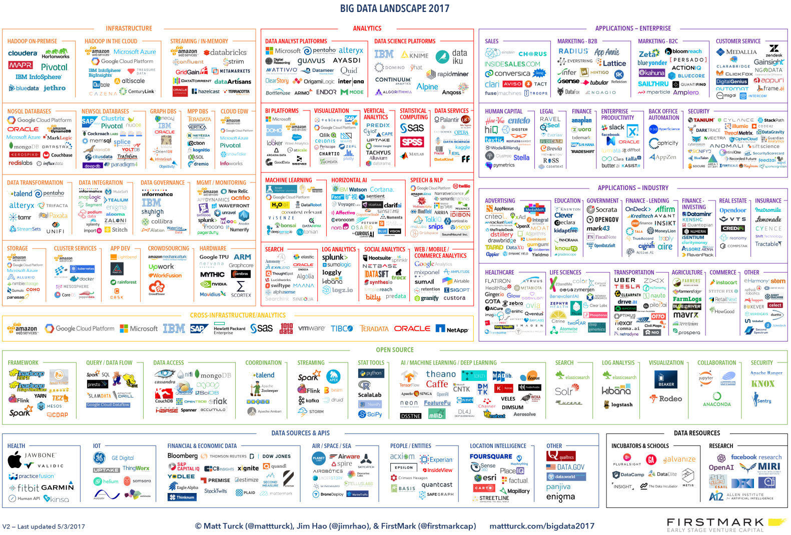
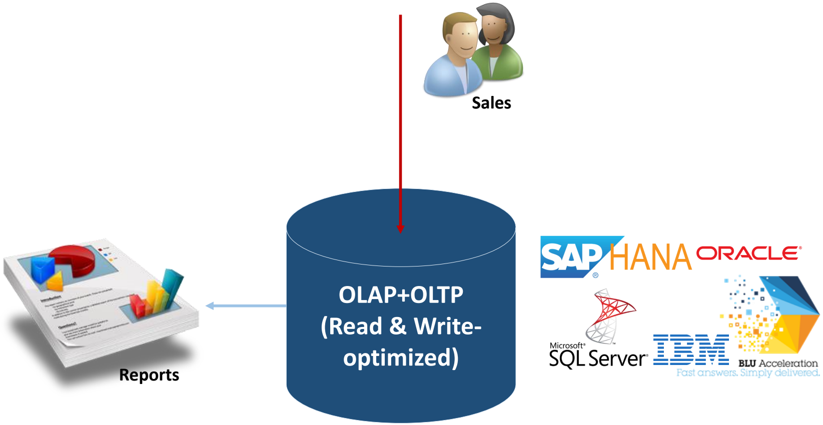
One Size Does not Fit All As of 2017



Data Management at Microscale: Volume & Velocity



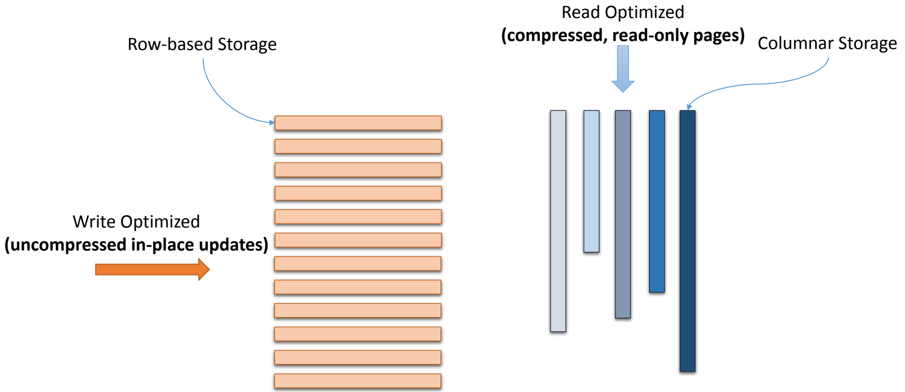
Sales

OLAP+OLTP (Read & Write-optimized)

Reports

Walmart

Storage Layout Conflict



Write-optimized (i.e., uncompressed & row-based) vs. read-optimized (i.e., compressed & column-based) layouts

Reducing Index maintenance: Velocity Dimension

Observed Trends

In the absence of in-place updates in operational multi-version databases, the cost of index maintenance becomes a major obstacle to cope with data velocity.

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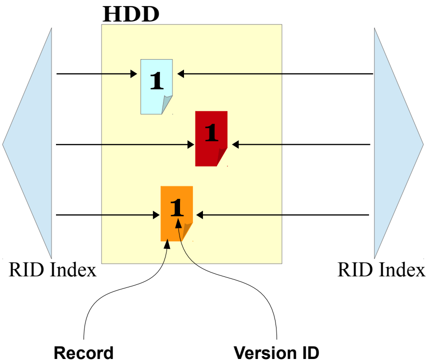
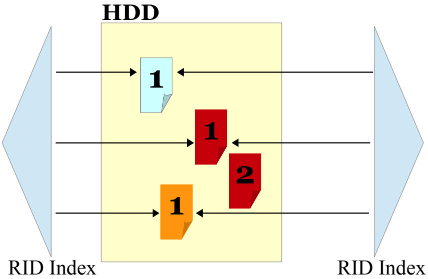
Extending storage hierarchy (using fast non-volatile memory) with *an extra level of indirection* in order to
Decouple Logical and Physical Locations of Records to
Reduce Index Maintenance

Traditional Multi-version Indexing: Updating Records



Updating random leaf pages

Traditional Multi-version Indexing: Updating Records



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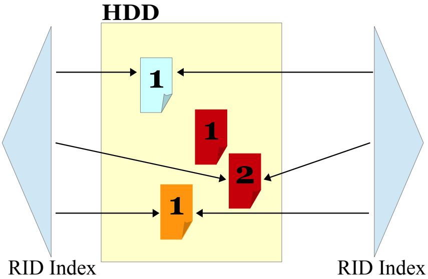

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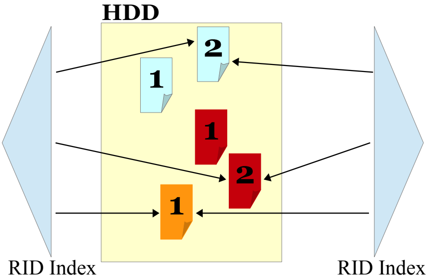

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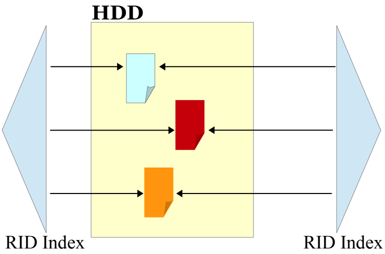
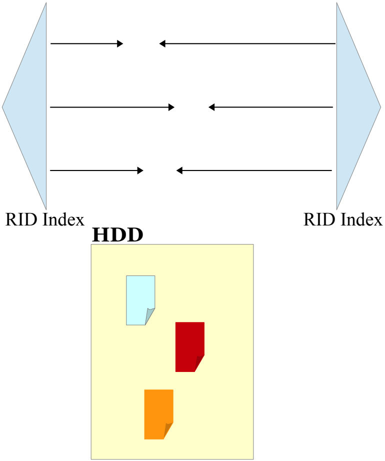
Indirection Indexing: Updating Records



Indirection Indexing: Updating Records



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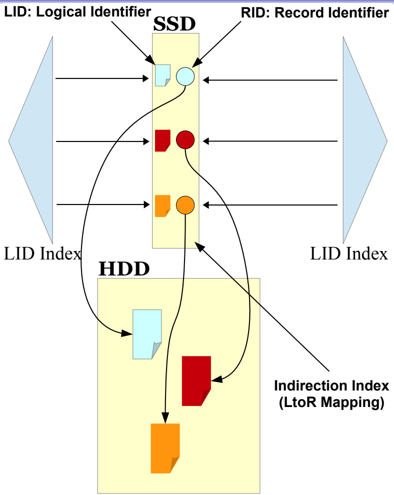

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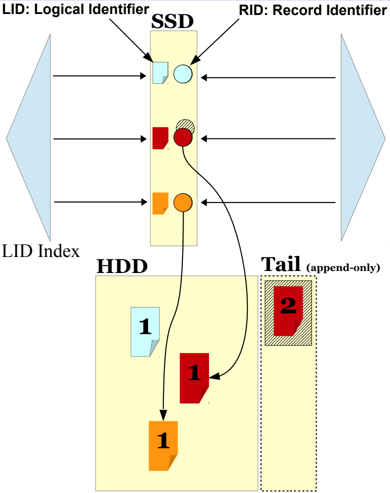
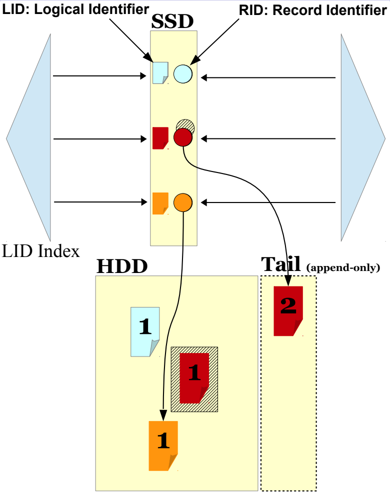


Eliminating random leaf-page updates

Indirection Indexing: Updating Records



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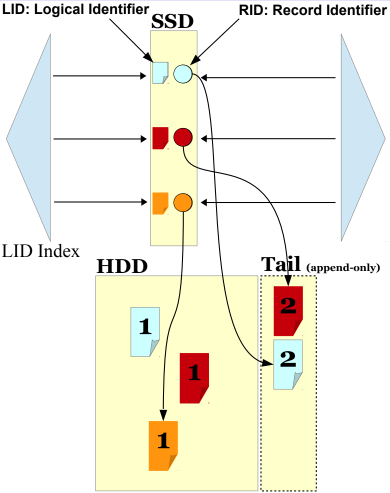

Eliminating random leaf-page updates

Unifying OLTP and OLAP: Velocity & Volume Dimensions

Observed Trends

In operational databases, there is a pressing need to close the gap between the write-optimized layout for OLTP (i.e., row-wise) and the read-optimized layout for OLAP (i.e., column-wise).

Unifying OLTP and OLAP: Velocity & Volume Dimensions

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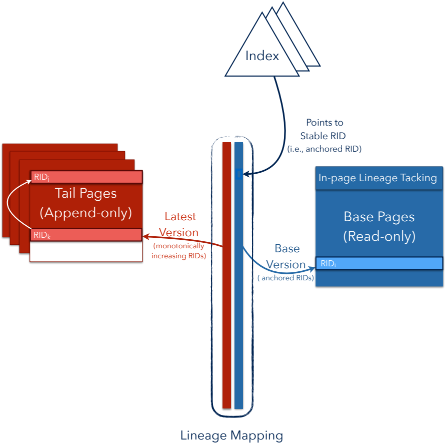
Introducing a *lineage-based storage architecture*, a contention-free update mechanism over a native columnar storage in order to

lazily and independently stage stable data from a write-optimized layout (i.e., OLTP) into a read-optimized layout (i.e., OLAP)

Lineage-based Storage Architecture (LSA): Intuition



Physical Update Independence: De-coupling data & its updates
(reconstruction via in-page lineage tracking and lineage mapping)

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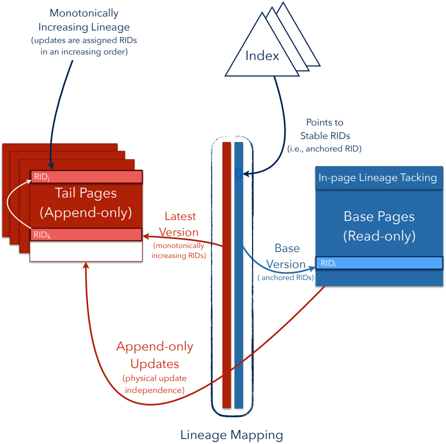

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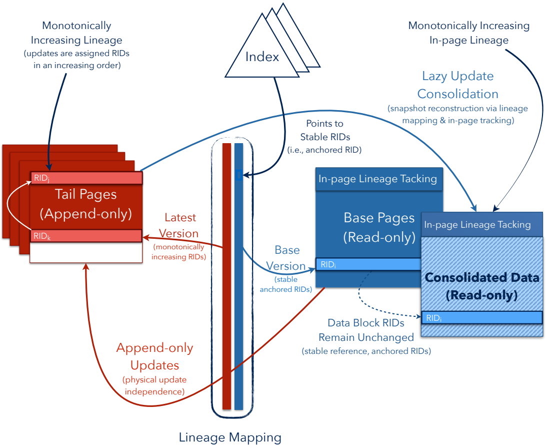
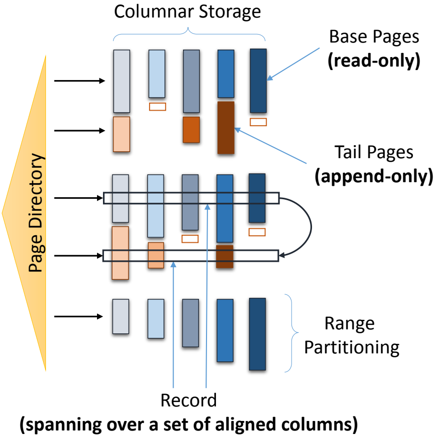

Monotonically Increasing Lineage
(updates are assigned RIDs in an increasing order)
Index
Monotonically Increasing In-page Lineage
Lazy Update Consolidation
(snapshot reconstruction via lineage mapping & in-page tracking)
Points to Stable RIDs
(i.e., anchored RID)
RID$_j$
Tail Pages
(Append-only)
RID$_k$
Latest Version
(monotonically increasing RIDs)
In-page Lineage Tacking
Base Pages
(Read-only)
RID$_i$
In-page Lineage Tacking
Consolidated Data
(Read-only)
RID$_i$
Base Version
(stable anchored RIDs)
Data Block RIDs Remain Unchanged
(stable reference, anchored RIDs)
Append-only Updates
(physical update independence)
Lineage Mapping

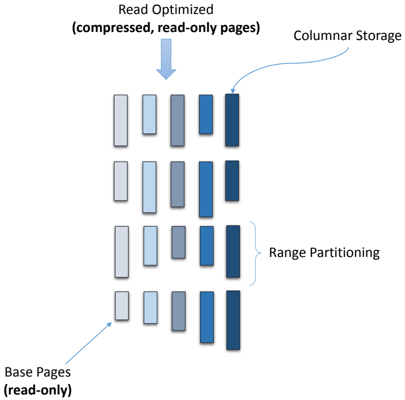
Physical Update Independence: De-coupling data & its updates
(reconstruction via in-page lineage tracking and lineage mapping)

Lineage-based Storage Architecture (LSA): Overview



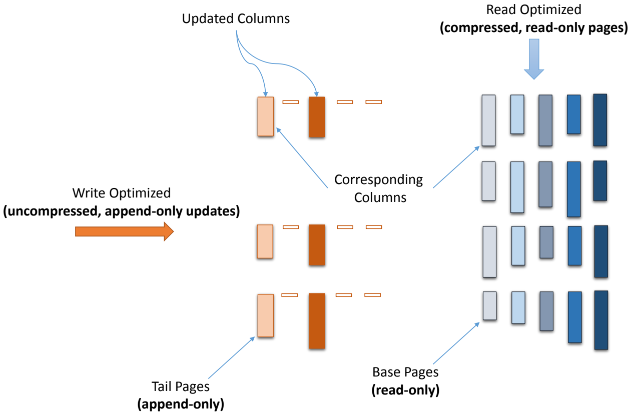
Overview of the lineage-based storage architecture
(**base pages** and **tail pages** are handled identically at the storage layer)

L-Store: Detailed Design



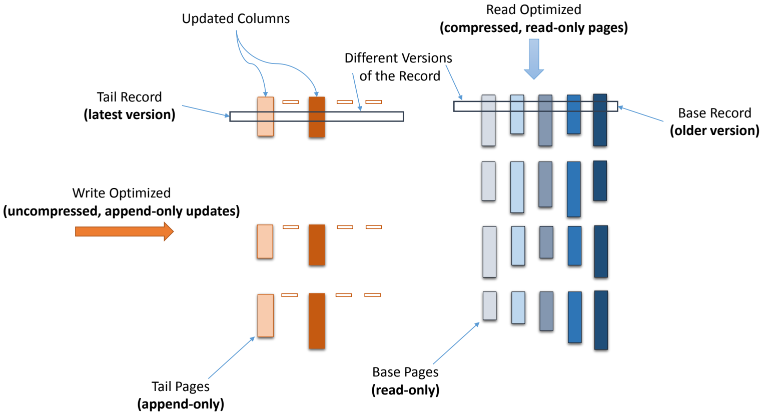
Records are range-partitioned and compressed into a set of ready-only **base pages** (accelerating analytical queries)

L-Store: Detailed Design



Recent updates for a range of records are clustered in their **tails pages** (transforming costly point updates into an amortized analytical-like query)

L-Store: Detailed Design



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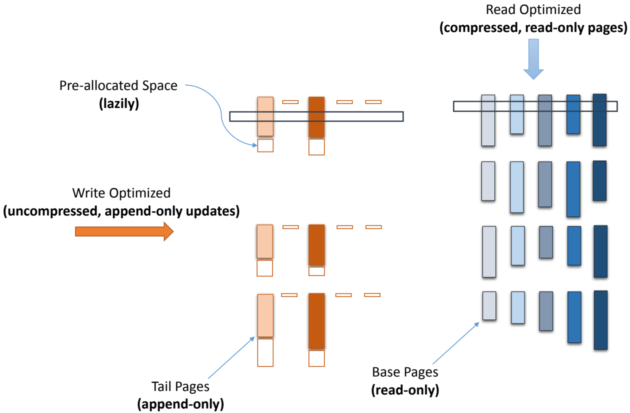
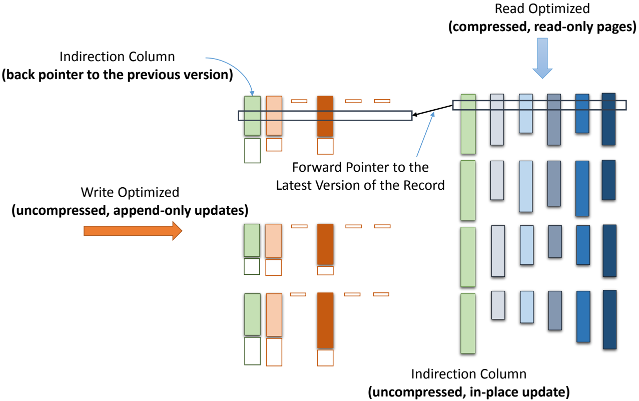


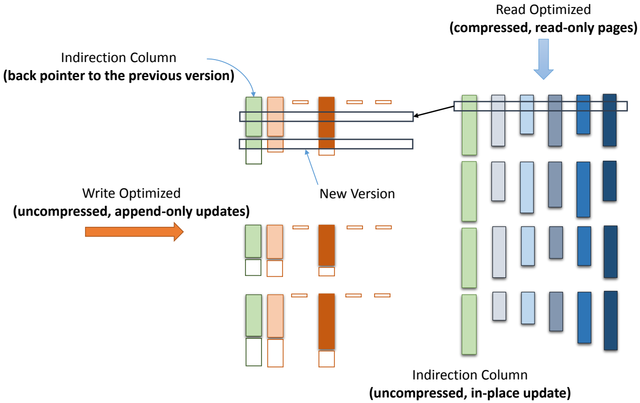
Recent updates are strictly appended, uncompressed in the pre-allocated space (eliminating the read/write contention)

L-Store: Detailed Design


Read Optimized
(compressed, read-only pages)
Indirection Column
(back pointer to the previous version)
Forward Pointer to the
Latest Version of the Record
Write Optimized
(uncompressed, append-only updates)
Indirection Column
(uncompressed, in-place update)

Achieving (at most) 2-hop access to the latest version of any record (avoiding read performance deterioration for point queries)

L-Store: Detailed Design


Read Optimized
(compressed, read-only pages)
Indirection Column
(back pointer to the previous version)
Write Optimized
(uncompressed, append-only updates)
New Version
Indirection Column
(uncompressed, in-place update)

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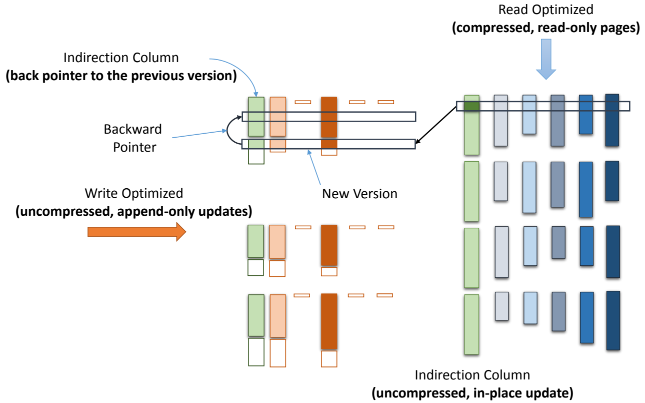
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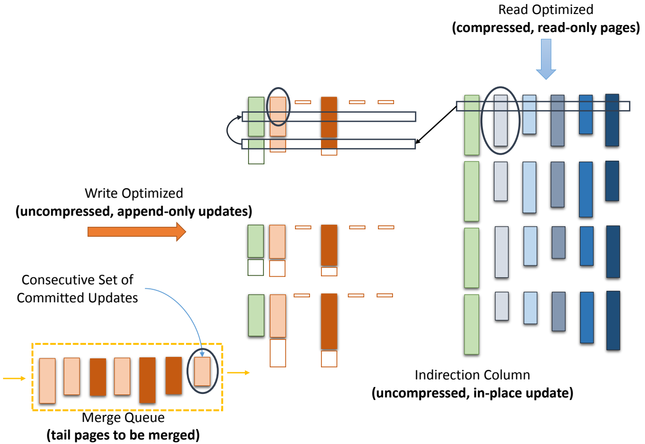
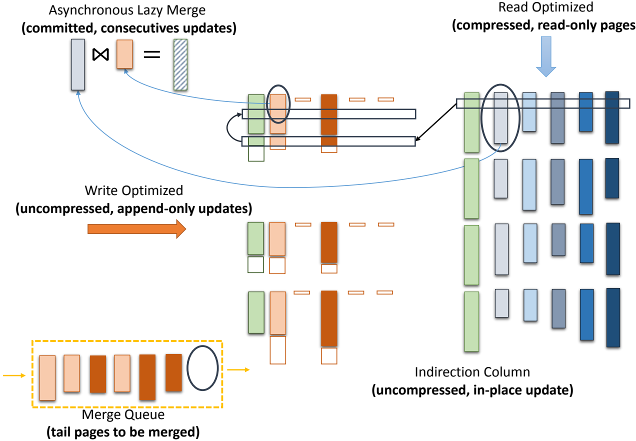
L-Store: Contention-free Merge


Read Optimized
(compressed, read-only pages)
Write Optimized
(uncompressed, append-only updates)
Consecutive Set of
Committed Updates
Merge Queue
(tail pages to be merged)
Indirection Column
(uncompressed, in-place update)

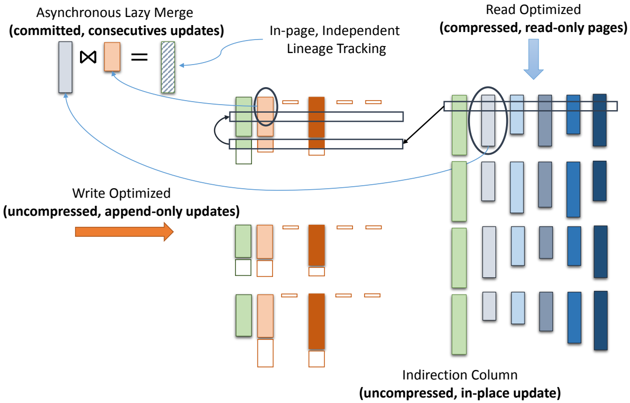
Contention-free merging of only stable data: read-only and committed data (no need to block on-going and new transactions)

L-Store: Contention-free Merge


Asynchronous Lazy Merge
(committed, consecutives updates)
⋈
=
Read Optimized
(compressed, read-only pages)
Write Optimized
(uncompressed, append-only updates)
Indirection Column
(uncompressed, in-place update)
Merge Queue
(tail pages to be merged)

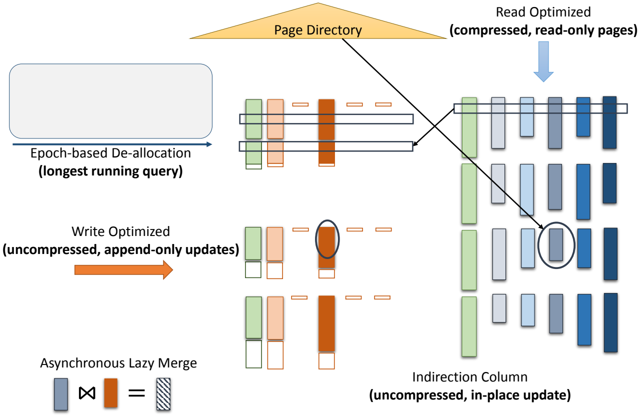
Lazy independent merging of **base pages** with their corresponding **tail pages** (resembling a local left outer-join of the base and tail pages)

L-Store: Contention-free Merge


Asynchronous Lazy Merge
(committed, consecutives updates)
⋈
=
In-page, Independent
Lineage Tracking
Read Optimized
(compressed, read-only pages)
Write Optimized
(uncompressed, append-only updates)
Indirection Column
(uncompressed, in-place update)

Independently tracking the lineage information within every page
(no need to coordinate merges among different columns of the same records)

L-Store: Epoch-based Contention-free De-allocation


Page Directory
Read Optimized
(compressed, read-only pages)
Epoch-based De-allocation
(longest running query)
Write Optimized
(uncompressed, append-only updates)
Asynchronous Lazy Merge
⋈
=
Indirection Column
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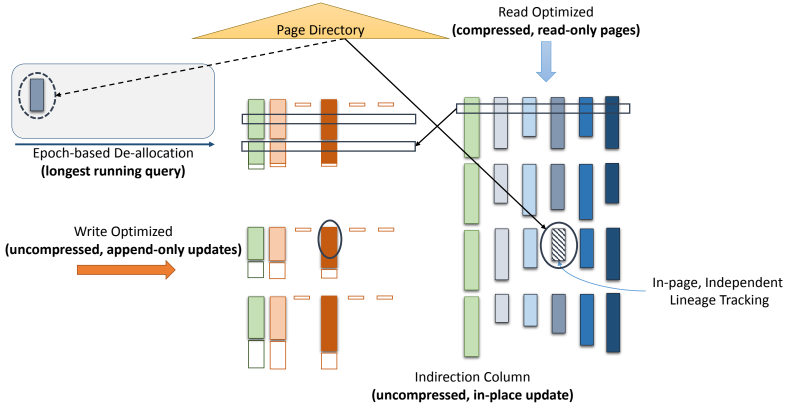
Contention-free page de-allocation using an epoch-based approach (no need to drain the ongoing transactions)

L-Store: Epoch-based Contention-free De-allocation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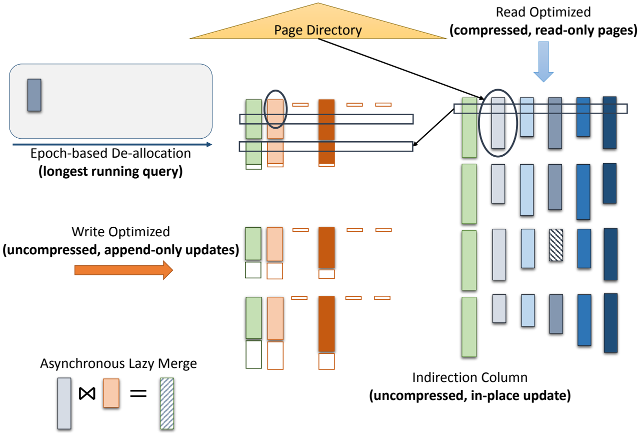
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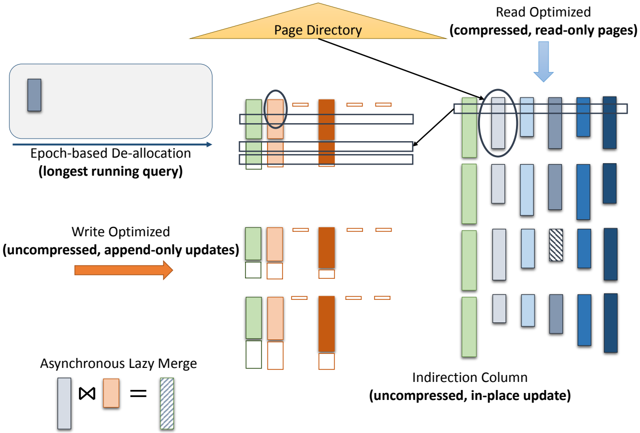
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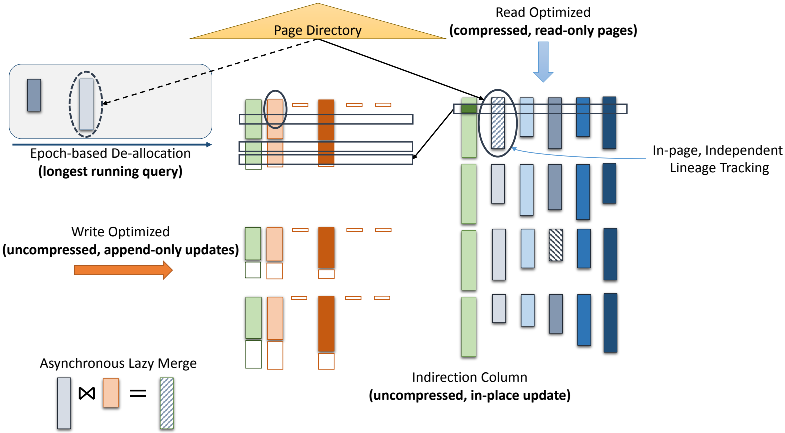


Contention-free page de-allocation using an epoch-based approach
(no need to drain the ongoing transactions)

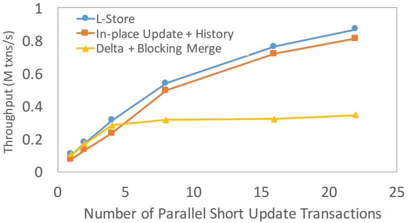
Experimental Analysis

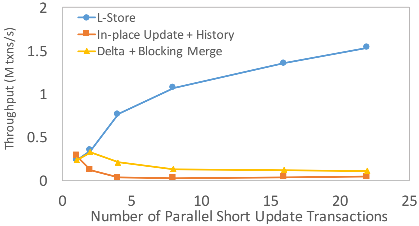
Experimental Settings

- Hardware:
  - 2 × 6-core Intel(R) Xeon(R) CPU E5-2430 @ 2.20GHz, 64GB, 15 MB L3 cache

- Workload: Extended Microsoft Hekaton Benchmark
  - Comparison with *In-place Update + History* and *Delta + Blocking Merge*
  - Effect of varying contention levels
  - Effect of varying the read/write ratio of short update transactions
  - Effect of merge frequency on scan
  - Effect of varying the number of short update vs. long read-only transactions
  - Effect of varying L-Store data layouts (row vs. columnar)
  - Effect of varying the percentage of columns read in point queries
  - Comparison with log-structured storage architecture (*LevelDB*)

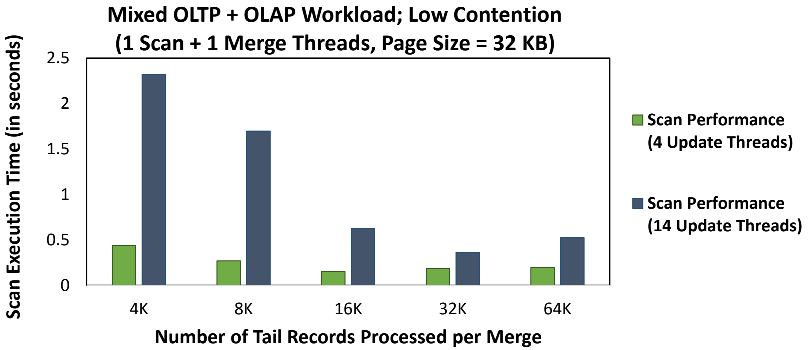
Effect of Varying Contention Levels





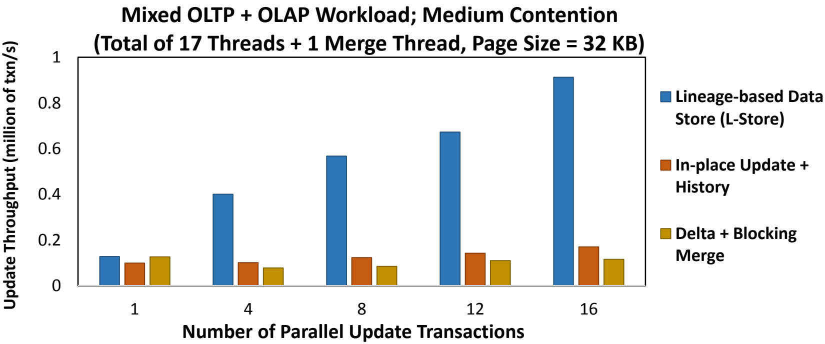
Achieving up to **40**× as increasing the update contention

Effect of Merge Frequency on Scan Performance



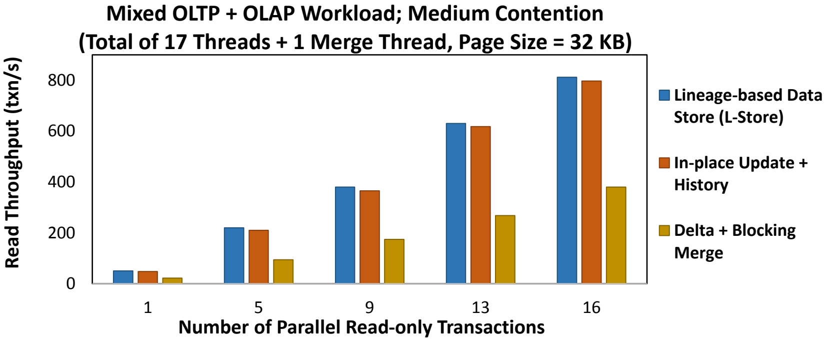
Merge process is essential in maintaining efficient scan performance

Effect of Mixed Workloads: Update Performance



Eliminating latching & locking results in a substantial performance improvement

Effect of Mixed Workloads: Read Performance



Coping with tens of update threads with a single merge thread

L-Store Key Contributions

- Unifying OLAP & OLTP by introducing lineage-based storage architecture (LSA)
- LSA is a native multi-version, columnar storage model that lazily & independently stages data from a write-optimized layout into a read-optimized one
- Contention-free merging of only stable data without blocking ongoing or incoming transactions
- Contention-free page de-allocation without draining ongoing transactions
- L-Store outperforms in-place update & delta approaches by factor of up to **8**× on mixed OLTP/OLAP workloads and up to **40**× on update-intensive workloads

Questions?

Thank you!

Exploratory Systems Lab (ExpoLab)
Website: https://expolab.org/

ExpoLab
Creativity Unfolded

ResilientDB
Security, Privacy Reloaded