Concurrency Protocols in L-Store

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Exploratory Systems Lab
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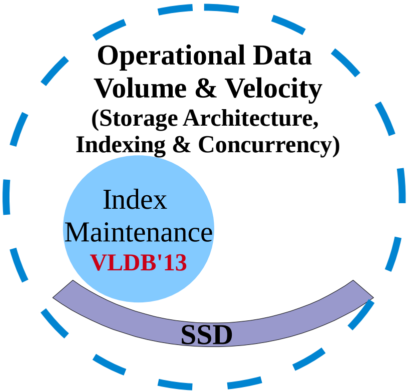
Extending Storage Hierarchy with Indirection Layer



Reducing Index maintenance: Velocity Dimension

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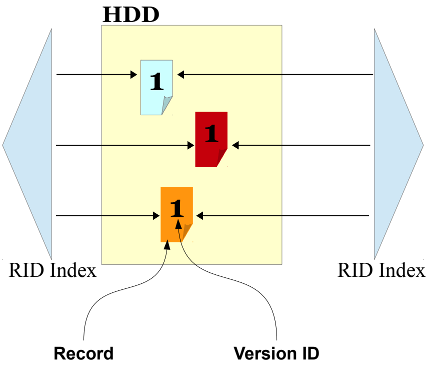
Decouple Logical and Physical Locations of Records to Reduce Index Maintenance

Traditional Multi-version Indexing: Updating Records



Updating random leaf pages

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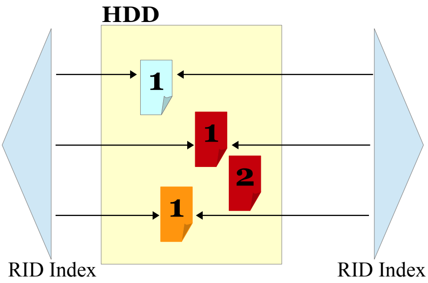

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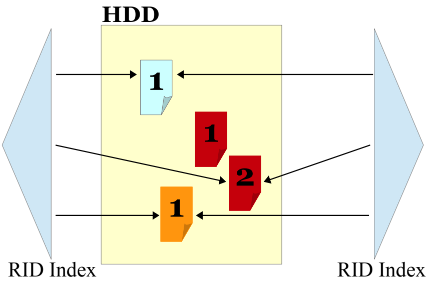

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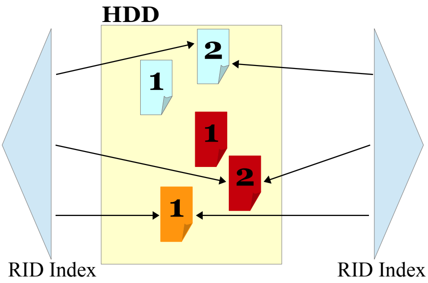

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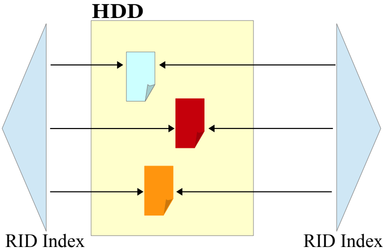

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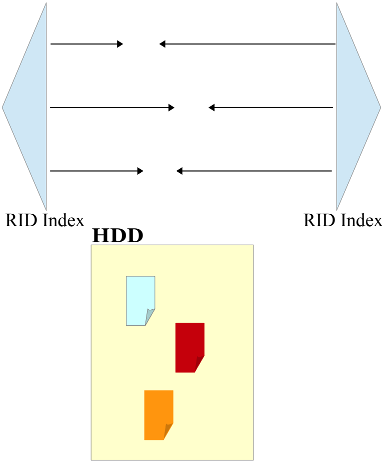

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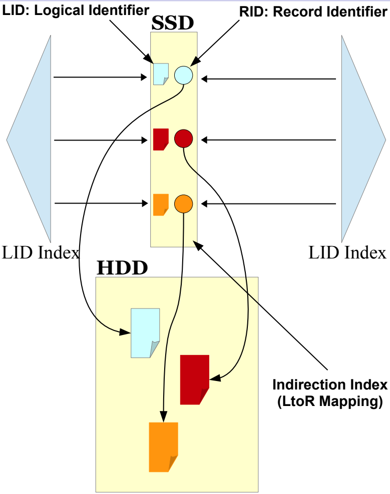

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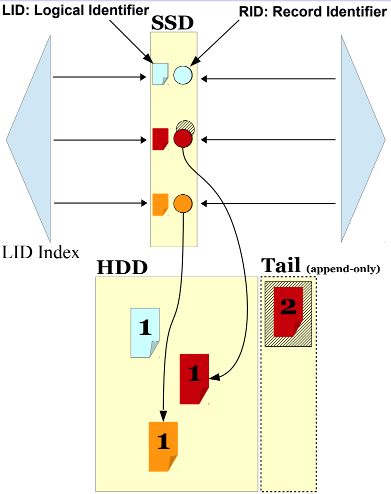

Eliminating random leaf-page updates

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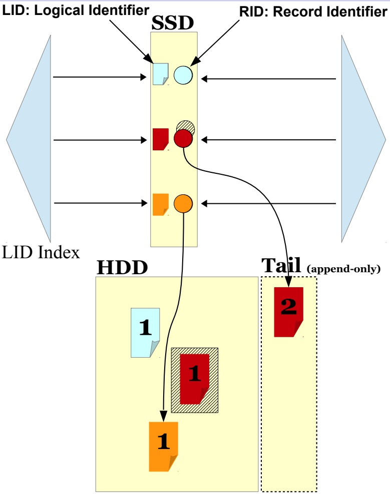

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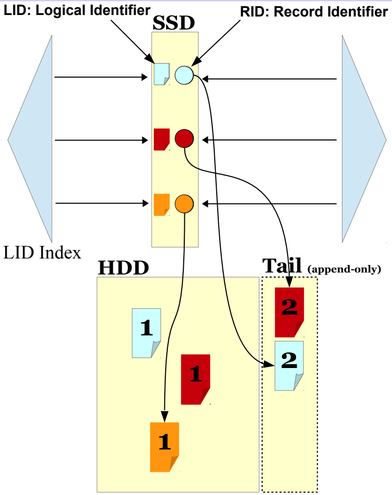


Eliminating random leaf-page updates

Analytical & Experimental Evaluations

Indirection Time Complexity Analysis

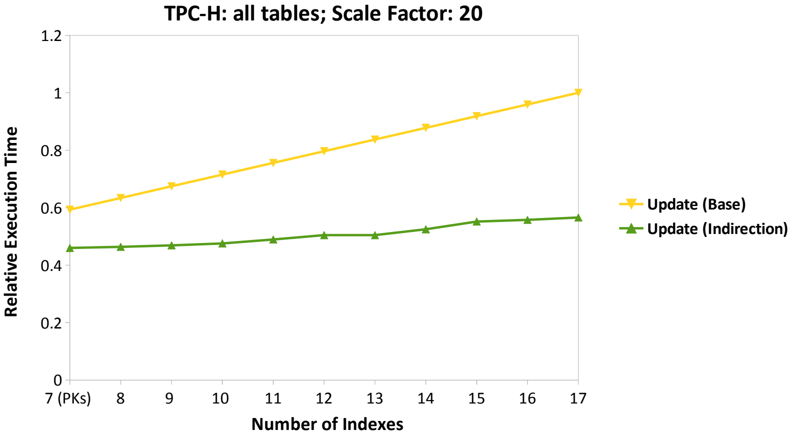
	Legend
K	Number of indexes
LB	LIDBlock size
M	Number of matching records

Method	Type	Imm. SSD	Def. SSD	Imm. HDD	Def. HDD
Base	Deletion	0	0	$2+K$	$\leq 1+K$
	Single-attr. update	**0**	**0**	$\mathbf{3+K}$	$\leq \mathbf{2+K}$
	Insertion	0	0	$1+K$	$\leq 1+K$
	Search Uniq.	0	0	2	0
	Search Mult.	0	0	$1+M$	0
Indirection	Deletion	2	0	2	≤ 3
	Single-attr. update	**2**	**0**	**4**	$\leq \mathbf{3}$
	Insertion	$2+2K$	$2K/LB$	1	$\leq 1+2K/LB$
	Search Uniq.	2	0	2	0
	Search Mult.	$1+M$	0	$1+M$	0

Experimental Setting

- Hardware:
  - (2 × 8-core) Intel(R) Xeon(R) CPU E7-4820 @ 2.00GHz, 32GB, 2 × HDD, SSD Fusion-io
- Software:
  - Database: IBM DB2 9.7
  - Prototyped in a commercial proprietary database
  - Prototyped in Apache Spark by UC Berkeley
  - LIBGist v.1.0: Generalized Search Tree C++ Library by UC Berkeley (**5K LOC**) (Predecessor of Generalized Search Tree (GiST) access method for PostgreSQL)
  - **LIBGist^{mv} Prototype:** Multi-version Generalized Search Tree C++ Library over LIBGist supporting Indirection/LIDBlock/DeltaBlock (**3K LOC**)
- Data:
  - TPC-H benchmark
  - Microsoft Hekaton micro benchmark

Indirection: Effect of Indexes in Operational Data Stores



Substantially improving the update time ...

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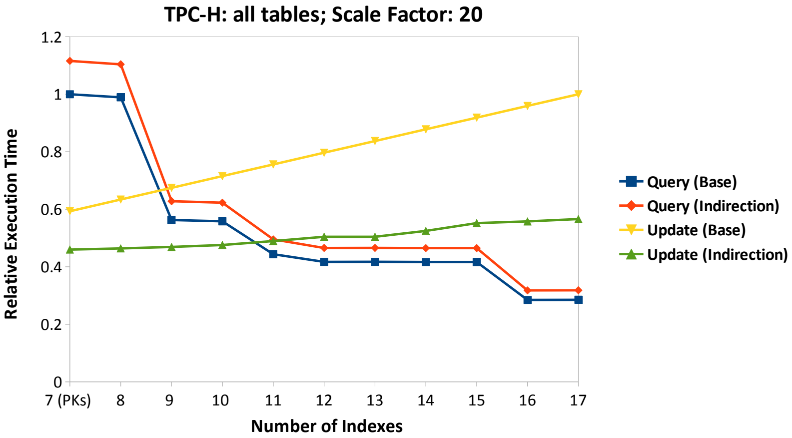
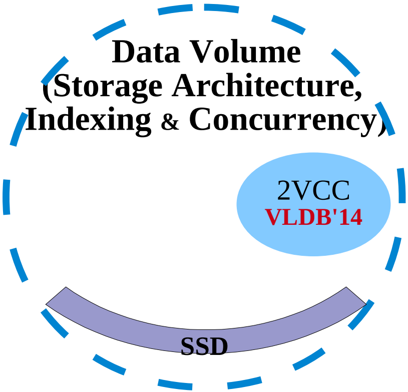


... Consequently affording more indexes and significantly reducing the query time

1. Data Velocity: Index Maintenance
2. Data Volume: MVCC Concurrency
3. Data Volume: Coordination-free Concurrency
4. Combining Volume & Velocity: Lineage-based Storage Architecture
5. Decentralized & Democratic Data Platform
6. Conclusions
7. References

Introducing Multi-version Concurrency Control



Generalized Concurrency Control: Volume Dimension

Observed Trends

In operational multi-version databases, there is a tremendous opportunity to avoid clashes between readers (scanning a large volume of data) and writers (frequent updates).

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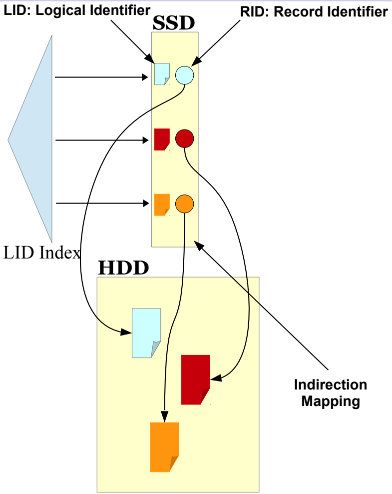
Decouple Readers/Writers to Reduce Contention
(Pessimistic and Optimistic Concurrency Control Coexistence)

2V-Indirection Indexing: Updating Records



Recap: Indirection technique for reducing index maintenance

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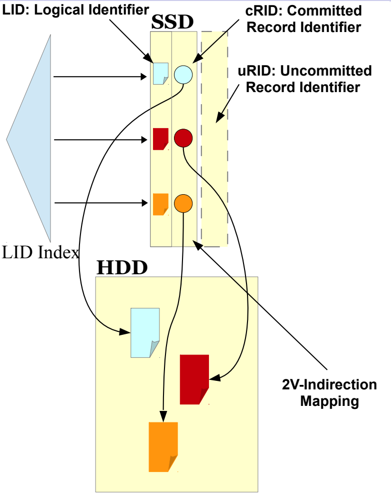

Extending the indirection to committed/uncommitted records

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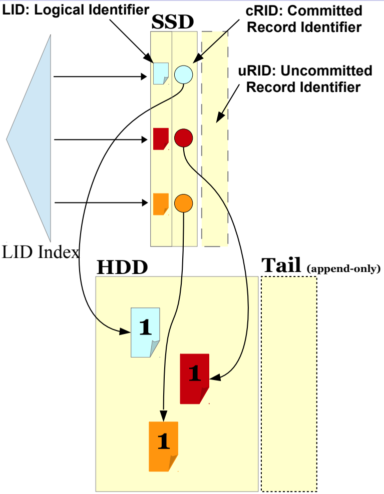

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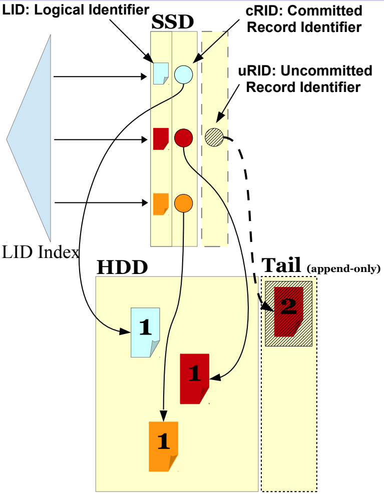

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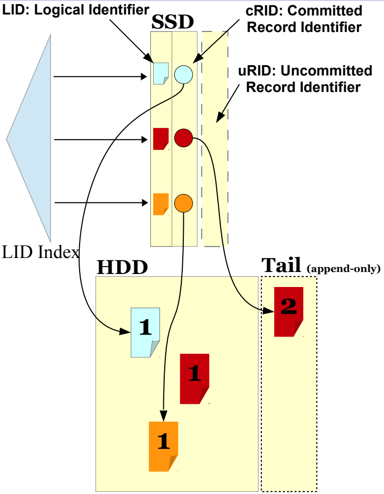

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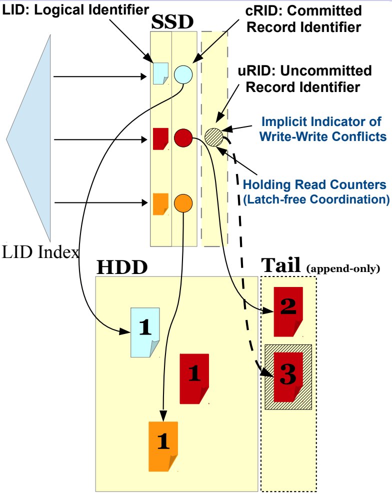
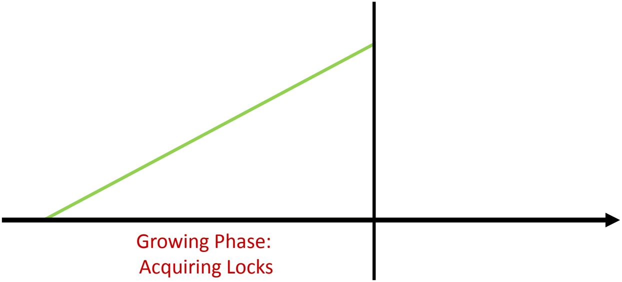


Decoupling readers/writers to eliminate contention

Overview of Two-version Concurrency Control Protocol



Two-phase locking (2PL) consisting of growing and shrinking phases

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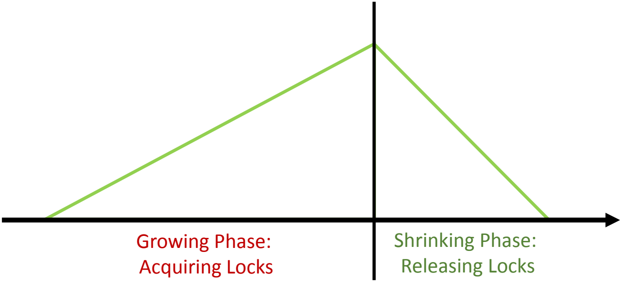

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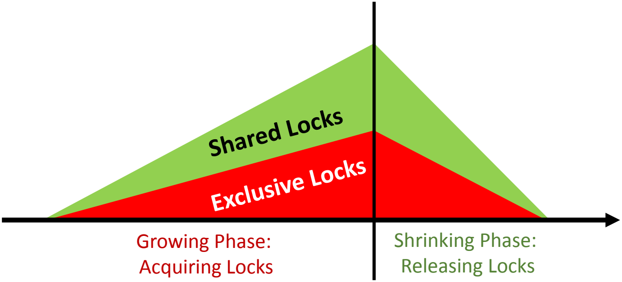

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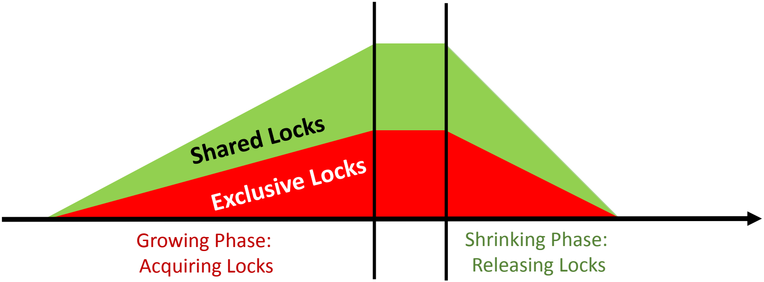

Extending 2PL with certify phase

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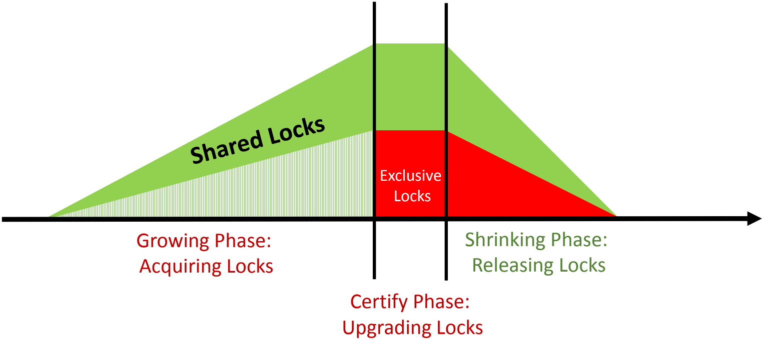

Exclusive locks held for shorter period (inherently optimistic)

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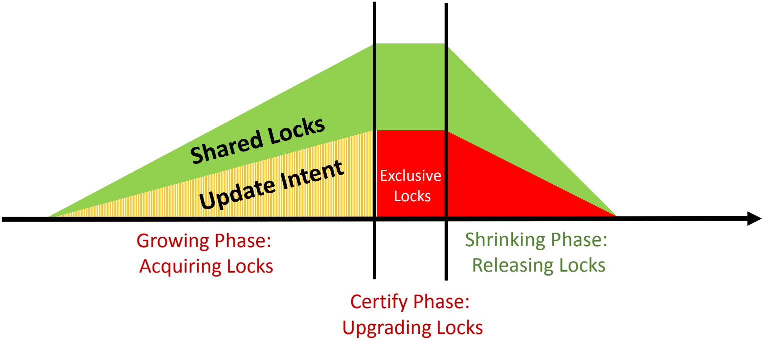

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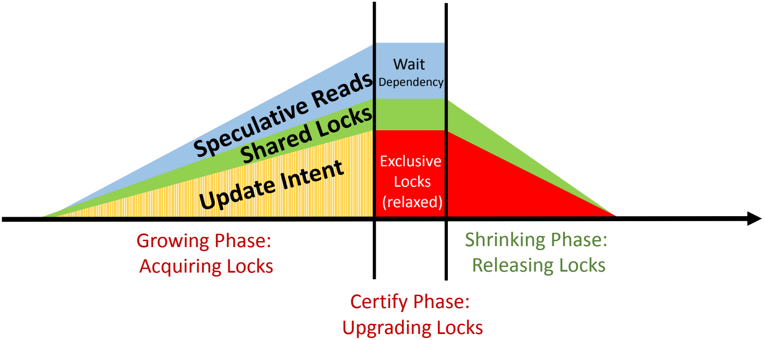

Relaxed exclusive locks to allow speculative reads (increased optimism)

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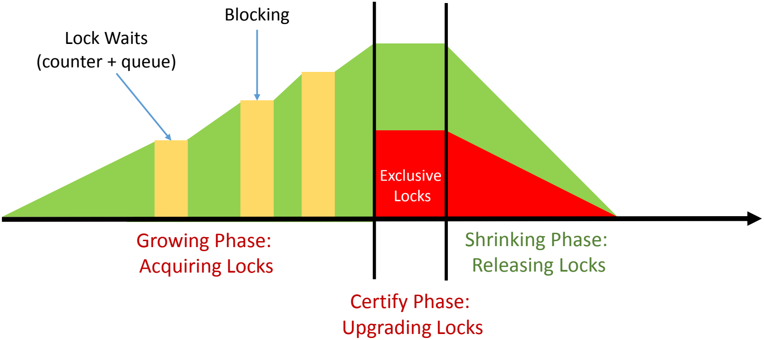
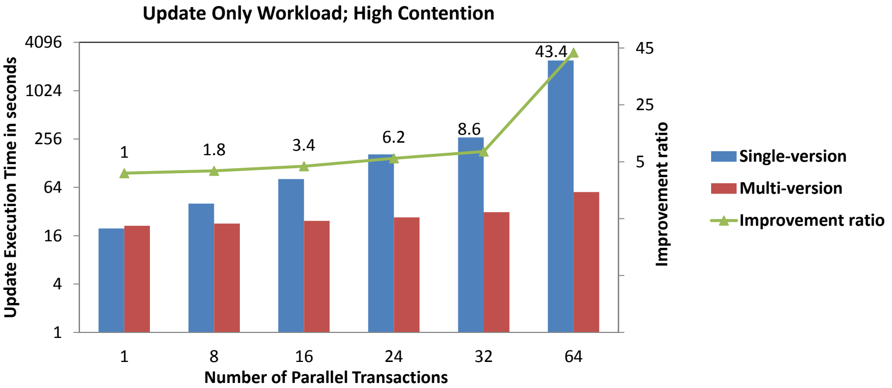


Trade-offs between blocking (i.e., locks) vs. non-blocking (i.e., read counters)

Experimental Analysis

2VCC: Effect of Parallel Update Transactions



Substantial gain by reducing the read/write contention & using non-blocking operations

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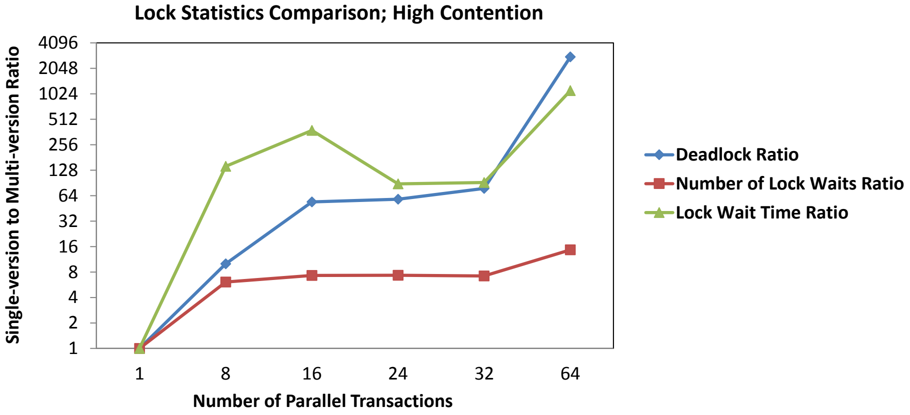

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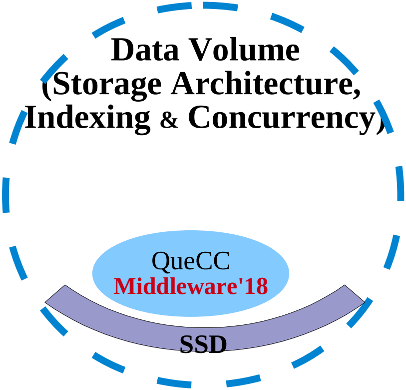
Introducing Coordination-free Concurrency Control



Confrontation-free Concurrency Control

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In operational databases, the use of pre-compiled stored procedures is predominant. There is a tremendous opportunity to exploit transaction prior knowledge to eliminate the need for coordination.

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Execution and Synchronization Decoupling

Queue-oriented, Control-free Concurrency (QueCC)

Batching Client Transactions

Execution & Synchronization Decoupling: Deterministic priority-based planning followed by queue-oriented execution

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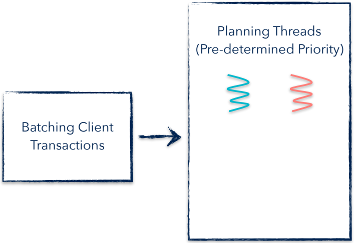

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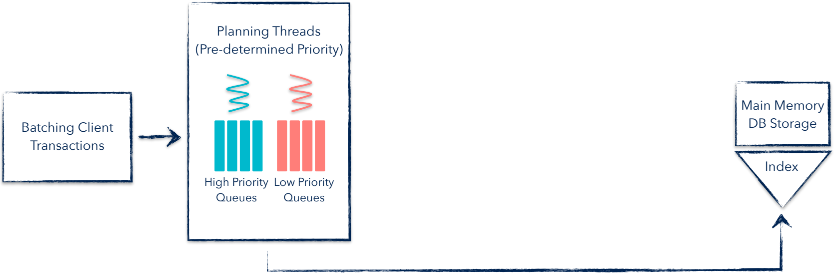

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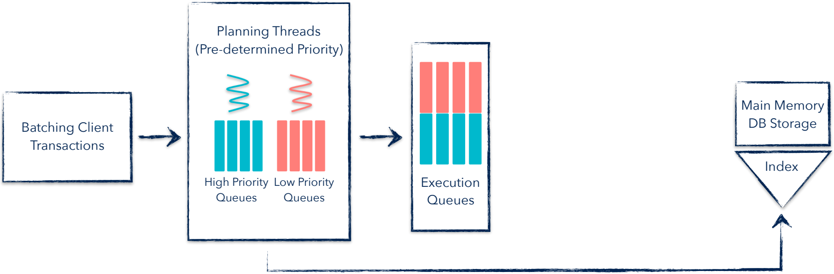

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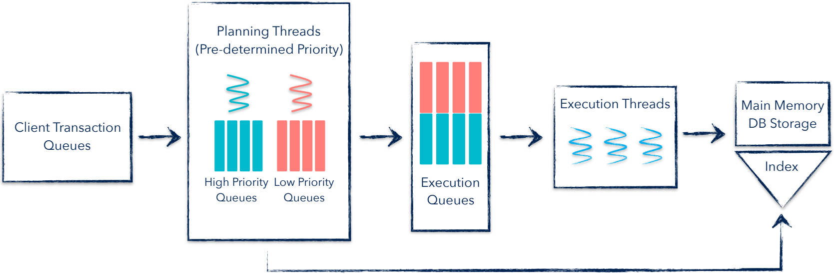

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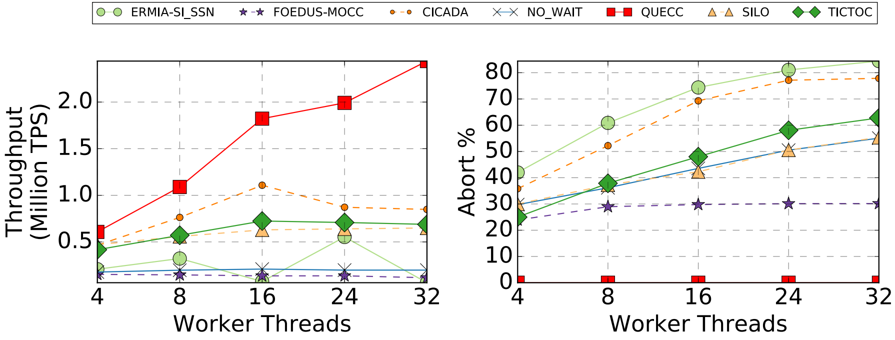
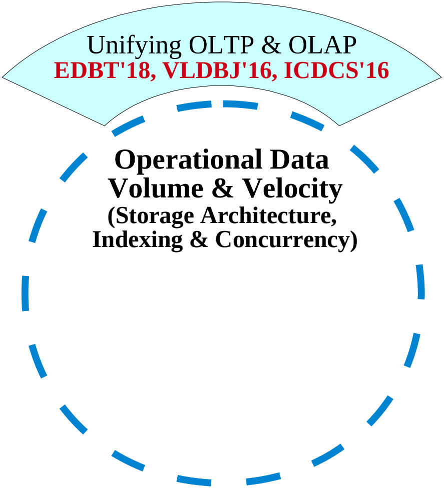


Avoiding thread coordination & eliminating all execution-induced aborts

Unifying OLTP and OLAP



Unifying OLTP and OLAP: Velocity & Volume Dimensions

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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).

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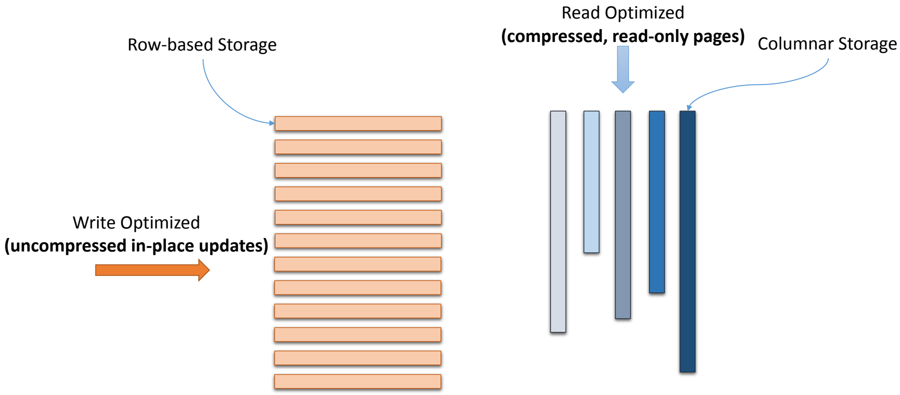
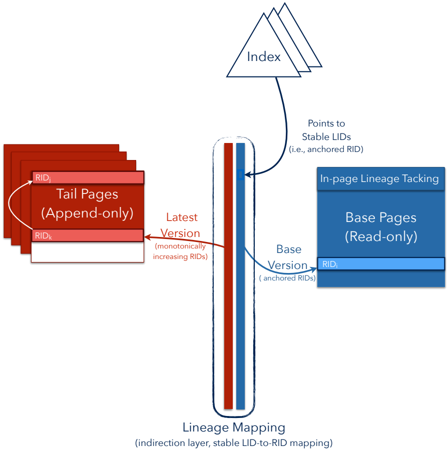
lazily and independently stage stable data from a write-optimized layout (i.e., OLTP) into a read-optimized layout (i.e., OLAP)

Storage Layout Conflict



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

Lineage-based Storage Architecture (LSA): Intuition



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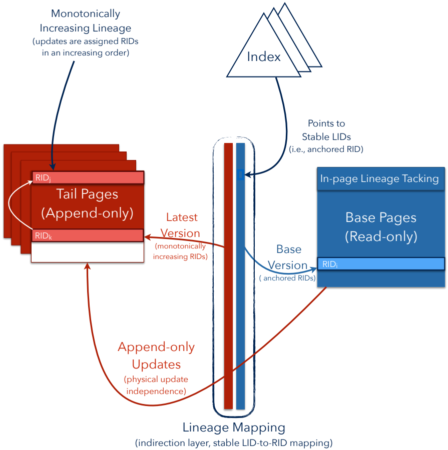

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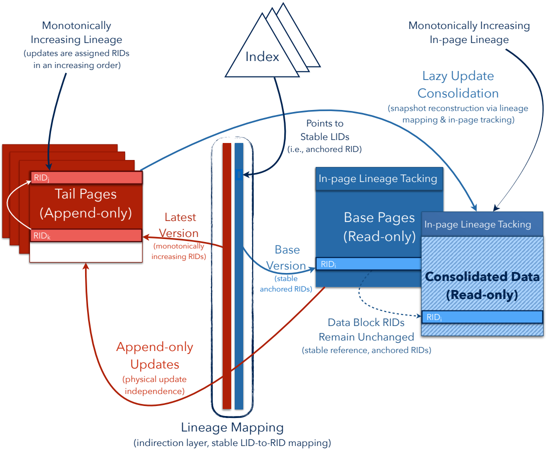

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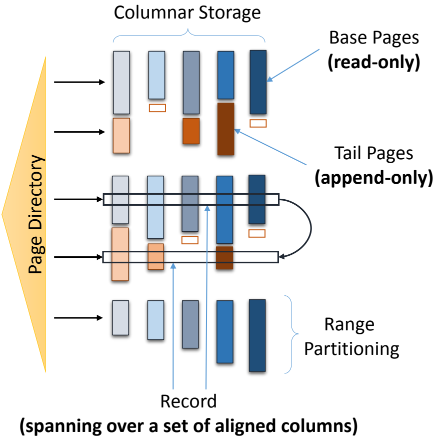
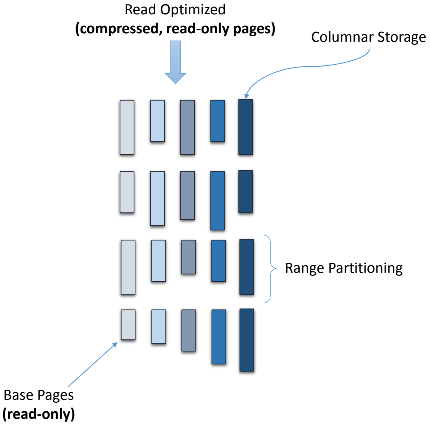


Overview of the lineage-based storage architecture
(**base pages** and **tail pages** are handled identically at the storage layer)

L-Store: Detailed Design



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

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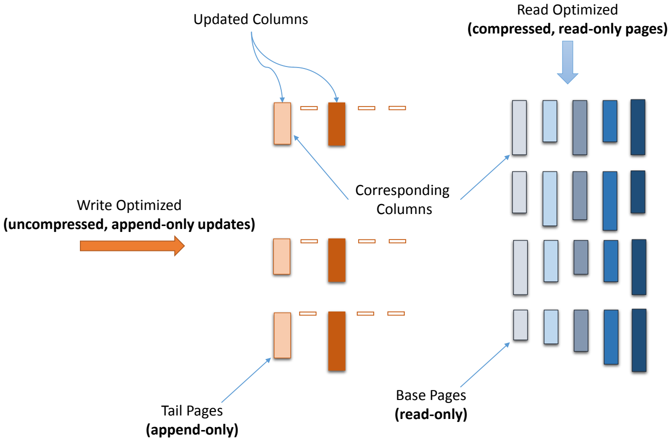

Recent updates for a range of records are clustered in their **tails pages** (transforming costly point updates into an amortized analytical-like query)

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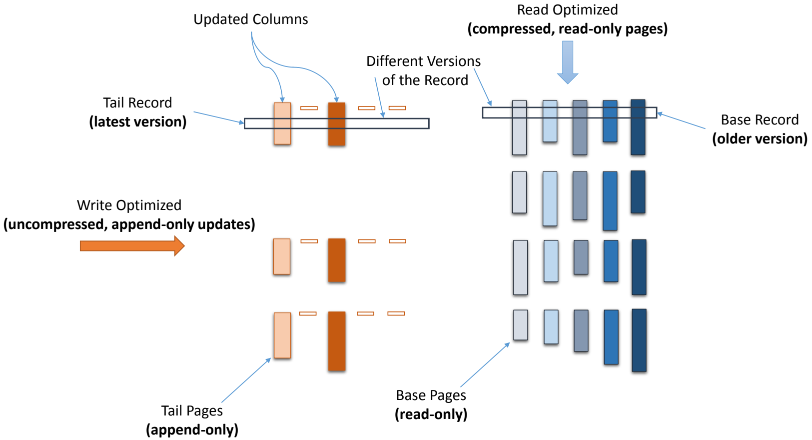

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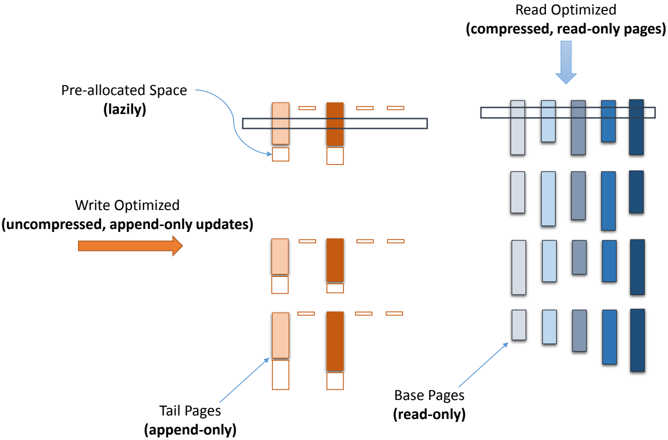

Recent updates are strictly appended, uncompressed in the pre-allocated space (eliminating the read/write contention)

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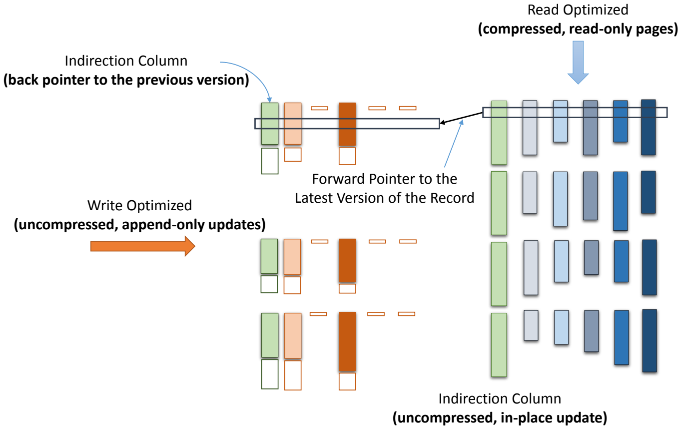
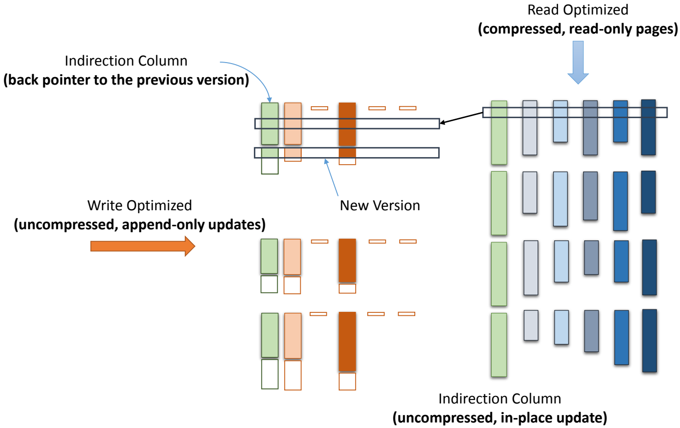


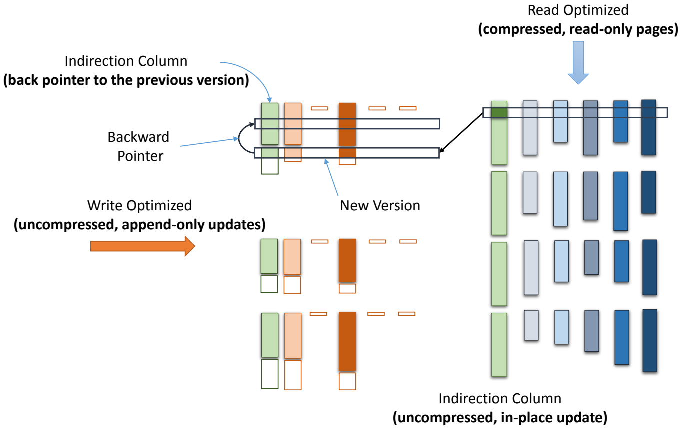
Achieving (at most) 2-hop access to the latest version of any record
(avoiding read performance deterioration for point queries)

L-Store: Detailed Design



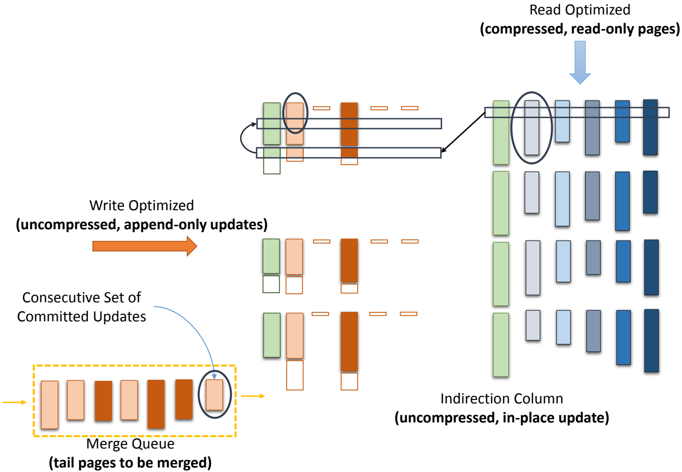
Achieving (at most) 2-hop access to the latest version of any record (avoiding read performance deterioration for point queries)

L-Store: Detailed Design



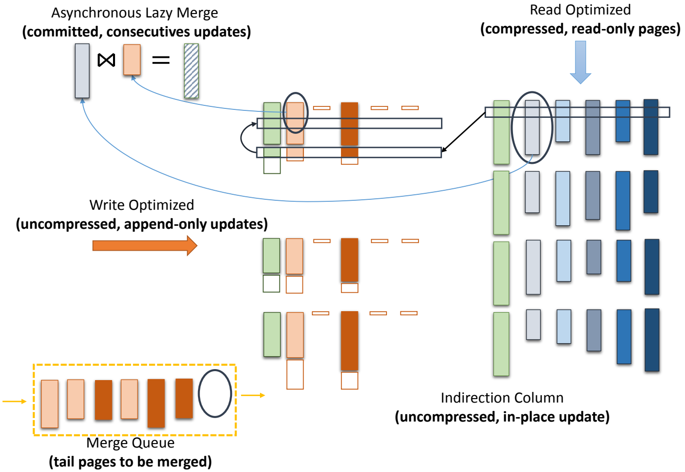
Achieving (at most) 2-hop access to the latest version of any record (avoiding read performance deterioration for point queries)

L-Store: Contention-free Merge



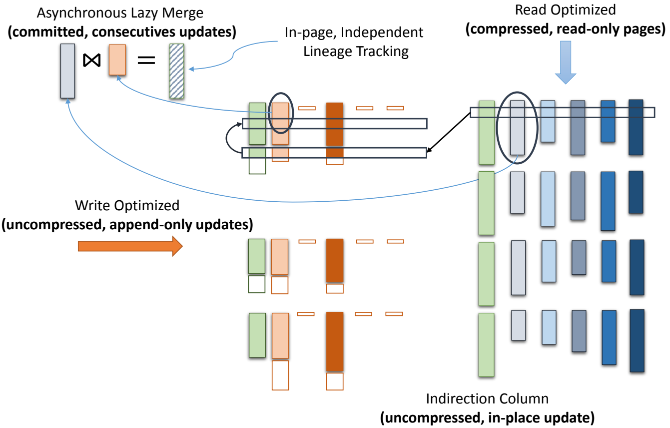
Contention-free merging of only stable data: read-only and committed data (no need to block on-going and new transactions)

L-Store: Contention-free Merge



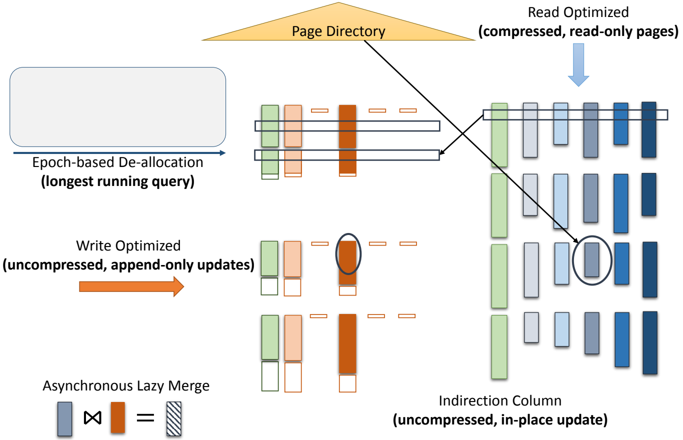
Lazy independent merging of **base pages** with their corresponding **tail pages** (resembling a local left outer-join of the base and tail pages)

L-Store: Contention-free Merge



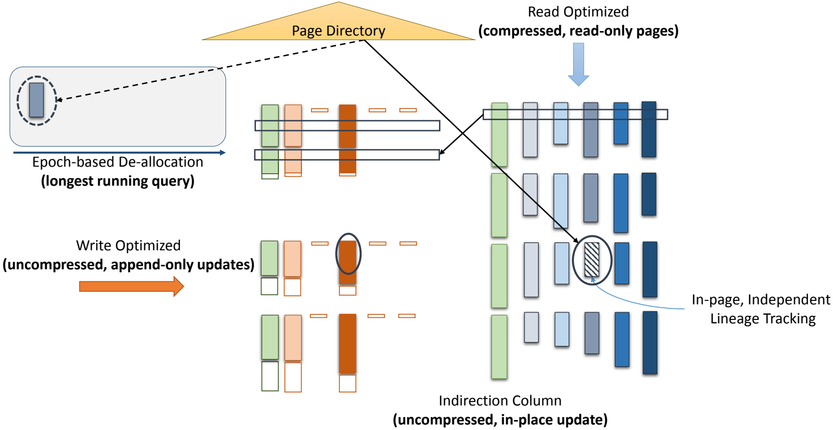
Independently tracking the lineage information within every page
(no need to coordinate merges among different columns of the same records)

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



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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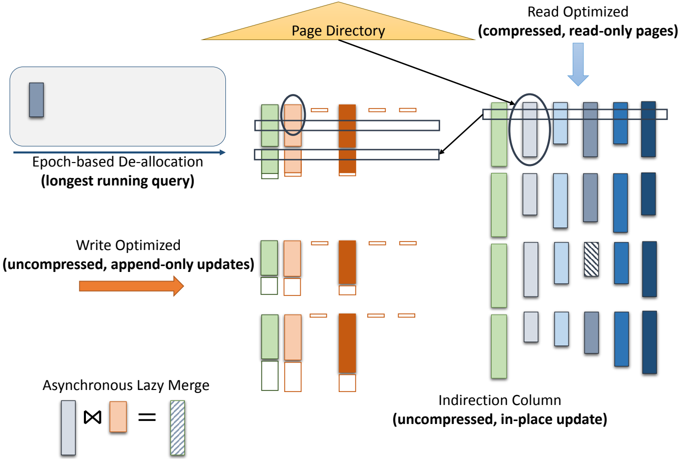

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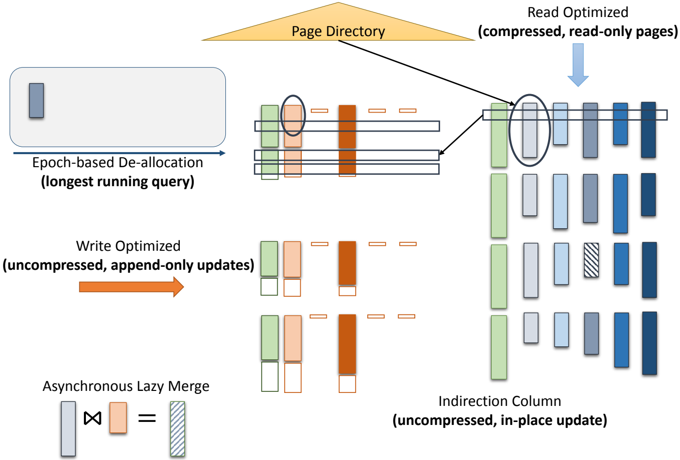

Contention-free page de-allocation using an epoch-based approach
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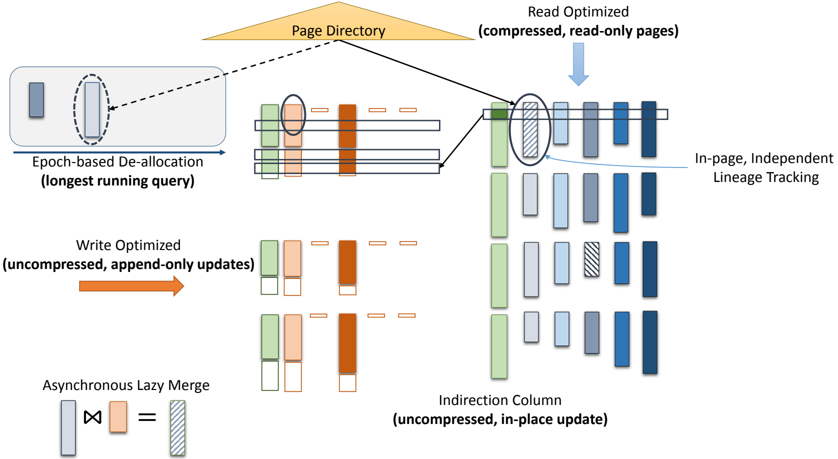


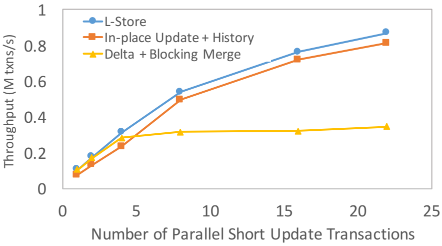
Contention-free page de-allocation using an epoch-based approach
(no need to drain the ongoing transactions)

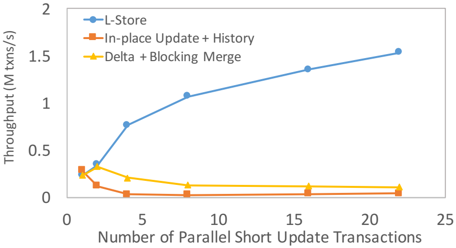
Experimental Analysis

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*)

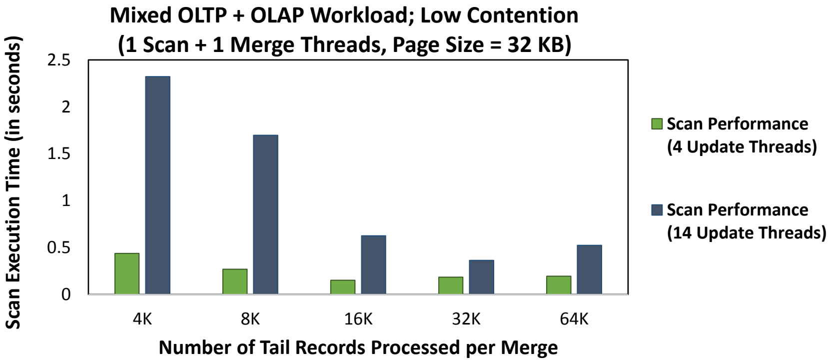
Effect of Varying Contention Levels





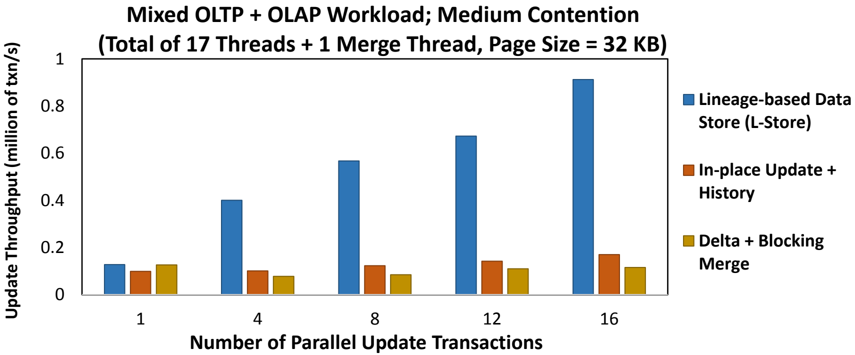
Achieving up to **40**× as increasing the update contention

Effect of Merge Frequency on Scan Performance



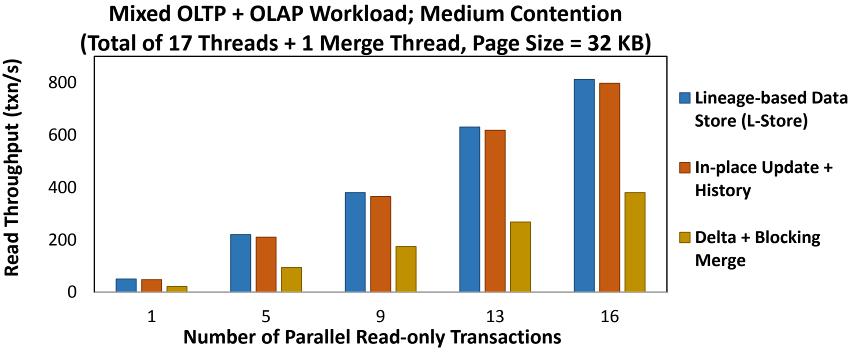
Merge process is essential in maintaining efficient scan performance

Effect of Mixed Workloads: Update Performance



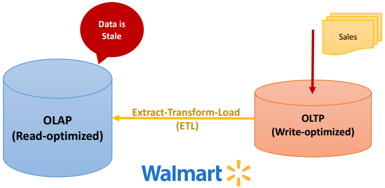
Eliminating latching & locking results in a substantial performance improvement

Effect of Mixed Workloads: Read Performance



Coping with tens of update threads with a single merge thread

Recap: Data Management Challenges at Microscale

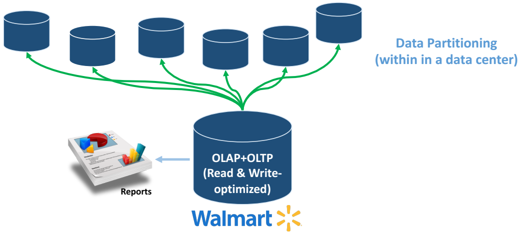


OLTP and OLAP data are isolated at microscale

Recap: Data Management Challenges at Microscale

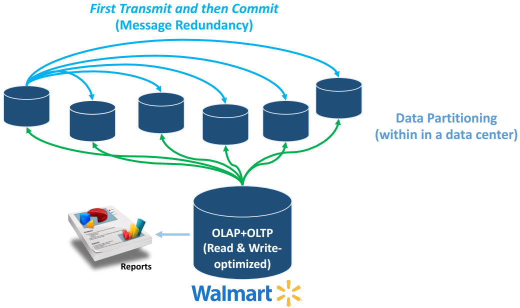
First step is to unify OLTP and OLAP

Platform Scaling: Data Partitioning



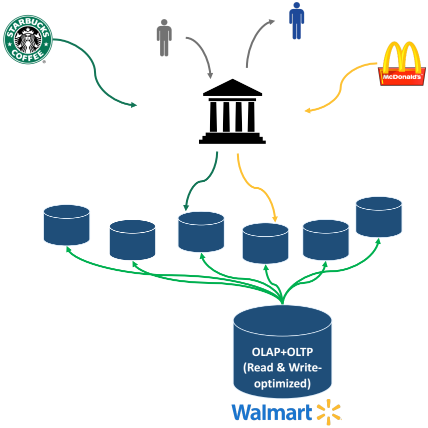
Moving towards distributed environment

Platform Scaling: Non-blocking Agreement Protocols



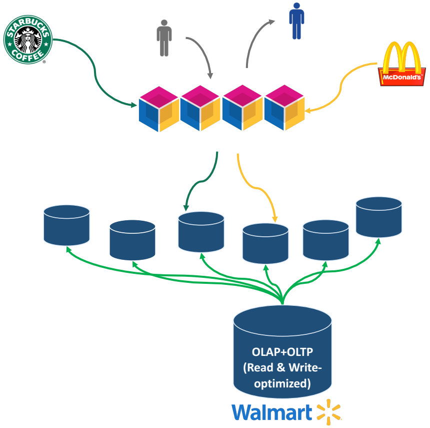
Message redundancy vs. latency trade-offs [EasyCommit, EDBT'18]

Central Control: Data Gate Keeper



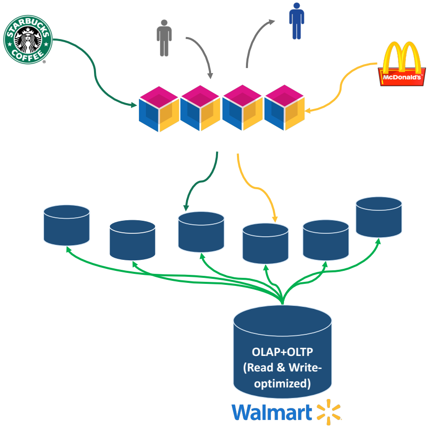
Conform to trusting the central authority and governance

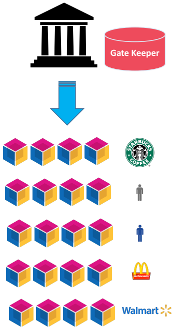
Decentralized Control: Removing Data Barrier



Seek trust in *decentralized* and *democratic* governance [PoE (under submission)]

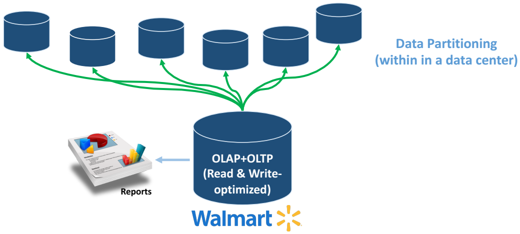
Democratic Control: Removing Trust Barrier





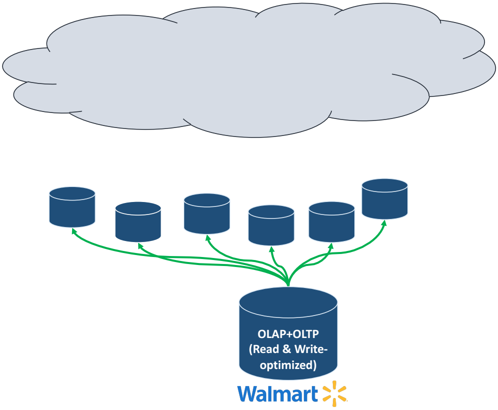
Seek trust in *decentralized* and *democratic* governance [PoE (under submission)]

Global-scale Reliable Platform over Unreliable Hardware



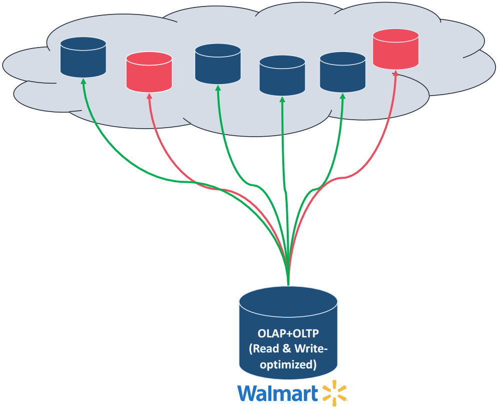
Self-managed infrastructure

Global-scale Reliable Platform over Unreliable Hardware



Cloud-managed infrastructure (trust the provider)

Global-scale Reliable Platform over Unreliable Hardware



Cloud-managed infrastructure (trust the provider)

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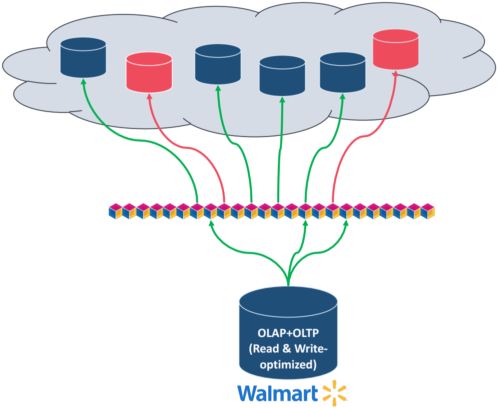
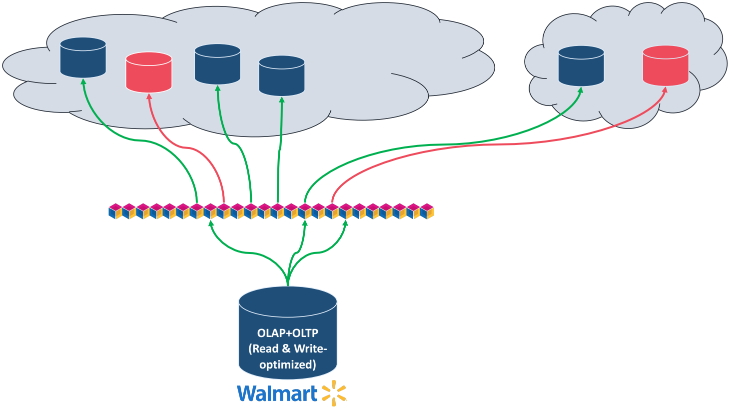


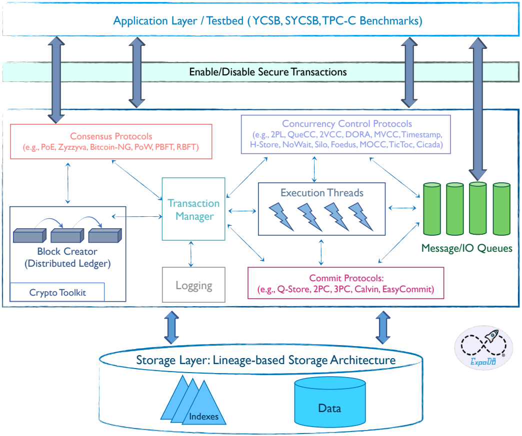
Light-weight, fault-tolerant, trusted middleware [Blockplane, (under submission)]

Global-scale Reliable Platform over Unreliable Hardware



Fault-tolerant protocols vs. consistency models [MultiBFT, GeoBFT (under submission)]

ExpoDB: Exploratory Data Platform Architecture



A decentralized & democratic platform to unify OLTP and OLAP

Contributions & Outlook

ExpoDB: Decentralized & Democratic Platform

- **Decentralized & Democratic Control**: PoE, MultiBFT, GeoBFT [under submission]
- **Reliability over Unreliable Hardware**: Blockplane [under submission]

Operational Data Stores: Velocity & Volume

- **Index Maintenance:** Indirection Technique **[VLDB'13, VLDBJ'16]**
- **Concurrency Control:** 2VCC Technique **[VLDB'14, Middleware'16],** EasyCommit **[EDBT'18],** QueCC **[Middleware'18]**
- **Hybrid Storage:** Enhancing Key-Value Store **[VLDB'12, ICDE'14]**
- **Real-time OLTP+OLAP:** Lineage-based Data Store (*L-Store*) **[EDBT-18,ICDCS'16, 30+ Patents]**

Stream Processing: Velocity

- **High-dimensional Indexing**: BE-Tree **[SIGMOD'11, TODS'13]**, Compressed Stream Processing **[ICDE'14]**
- **(Distributed) Top-*k* Indexing**: BE*-Tree **[ICDE'12, ICDCS'13, Middleware'17, ICDCS'17]**
- **Hardware Acceleration**: FPGAs **[VLDB'10, ICDE'12, VLDB'13, ICDE'15, SIGMOD Record'15, ICDE'16, USENIX ATC'16, ICDCS'17, ICDE'18]**
- **Novel Mappings**: XML/XPath **[EDBT'11]**, Distributed Workflow **[TDKE'15, SIGMOD'15, ICDE'16, Middleware'16]**

Questions?

Thank you!

Exploratory Systems Lab (ExpoLab)
Website: https://msadoghi.github.io/

ExpoLab
Creativity Unfolded

ExpoDB

Related Publications (Patents Omitted)

I. Abdelaziz, A. Fokoue, O. Hassanzadeh, P. Zhang, M. Sadoghi.
Large-scale structural and textual similarity-based mining of knowledge graph to predict drug-drug interactions.
In *J. Web Sem.* pages 104–117, 2017.

A. Fokoue, O. Hassanzadeh, **M. Sadoghi**, and P. Zhang.
Predicting drug-drug interactions through similarity-based link prediction over web data.
In *Proceedings of the 25th International Conference on World Wide Web, WWW 2016, Montreal, Canada, April 11-15, 2016, Companion Volume*, pages 175–178, 2016.

A. Fokoue, **M. Sadoghi**, O. Hassanzadeh, and P. Zhang.
Predicting drug-drug interactions through large-scale similarity-based link prediction.
In *The Semantic Web. Latest Advances and New Domains - 13th International Conference, ESWC 2016, Heraklion, Crete, Greece, May 29 - June 2, 2016, Proceedings*, pages 774–789, 2016.

Rajesh R. Bordawekar and **M. Sadoghi**.
Accelerating database workloads by software-hardware-system co-design.
In *32nd IEEE International Conference on Data Engineering, ICDE 2016, Helsinki, Finland, May 16-20, 2016*, pages 1428–1431, 2016.

A. Chandel, O. Hassanzadeh, N. Koudas, **M. Sadoghi**, and D. Srivastava.
Benchmarking declarative approximate selection predicates.
In *Proceedings of the 2007 ACM SIGMOD International Conference on Management of Data*, SIGMOD 2007, pages 353–364, New York, NY, USA, 2007. ACM.

A. Farroukh, **M. Sadoghi**, and H.-A. Jacobsen.
Towards vulnerability-based intrusion detection with event processing.
In *Proceedings of the 5th ACM international conference on Distributed event-based system*, DEBS 2011, pages 171–182, New York, New York, USA, 2011. ACM.

O. Hassanzadeh, **M. Sadoghi**, and R. J. Miller.
Accuracy of approximate string joins using grams.
In V. Ganti and F. Naumann, editors, *Proceedings of the Fifth International Workshop on Quality in Databases, QDB 2007 at VLDB 2007 conference, Vienna, Austria, September 23, 2007*, pages 11–18, 2007.

M. Hemmatpour, B. Montrucchio, M. Rebaudengo, and **M. Sadoghi**.
Kanzi: A distributed, in-memory key-value store.
In *Proceedings of the 17th Annual Middleware Conference, Trento, Italy, December 1216, 2016*, 2016.

M. Jergler, **M. Sadoghi**, and H.-A. Jacobsen.
D2WORM: A management infrastructure for distributed data-centric workflows.
In *Proceedings of the 2015 ACM SIGMOD International Conference on Management of Data, Melbourne, Victoria, Australia, May 31 - June 4, 2015*, pages 1427–1432, 2015.

M. Jergler, **M. Sadoghi**, and H.-A. Jacobsen.
Geo-distribution of flexible business processes over publish/subscribe paradigm.
In *Proceedings of the 17th Annual Middleware Conference, Trento, Italy, December 1216, 2016*, 2016.

P. Menon, T. Rabl, **M. Sadoghi**, and H. Jacobsen.
CaSSanDra: An SSD boosted key-value store.
In *IEEE 30th International Conference on Data Engineering, Chicago, ICDE 2014, IL, USA, March 31 - April 4, 2014*, pages 1162–1167, 2014.

P. Menon, T. Rabl, **M. Sadoghi**, and H. Jacobsen.
Optimizing key-value stores for hybrid storage architectures.
In *the 24th International Conference of Center for Advanced Studies on Collaborative Research, IBM CASCON 2014. Toronto, Canada, November 3-5, 2014*. 2014.

N. Mohammadreza, **M. Sadoghi**, and H.-A. Jacobsen.
The FQP vision: Flexible query processing on a reconfigurable computing fabric.
SIGMOD Record - Special Issue on Visionary Ideas in Data Management , 44(2), pages 5–10, 2015.

V. Muthusamy, Y. Yoon, **M. Sadoghi**, and H.-A. Jacobsen.
eQoSystem: supporting fluid distributed service-oriented workflows.
In *Proceedings of the 5th ACM international conference on Distributed event-based system*, DEBS 2011, pages 381–382, New York, New York, USA, 2011. ACM.

M. Najafi, **M. Sadoghi**, and H. Jacobsen.
Flexible query processor on FPGAs.
PVLDB 2013, 6(12):1310–1313, 2013.

M. Najafi, **M. Sadoghi**, and H. Jacobsen.
Configurable hardware-based streaming architecture using online programmable-blocks.
In *the 31st IEEE International Conference on Data Engineering, ICDE 2015, Seoul, South Korea, April 13-17, 2015*, pages 819–830, 2015.

M. Najafi, **M. Sadoghi**, and H. Jacobsen.
The FQP vision: Flexible query processing on a reconfigurable computing fabric.
SIGMOD Record, 44(2):5–10, 2015.

M. Najafi, **M. Sadoghi**, and H. Jacobsen.
Splitjoin: A scalable, low-latency stream join architecture with adjustable ordering precision.
In *2016 USENIX Annual Technical Conference, USENIX ATC 2016, Denver, CO, USA, June 22-24, 2016.*, pages 493–505, 2016.

T. Rabl, **M. Sadoghi**, S. Gómez-Villamor, V. Muntés-Mulero, H.-A. Jacobsen, and S. Mankovskii.
Solving big data challenges for enterprise application performance management.
Proceedings of the VLDB Endowment, PVLDB 2012, 5(12):1724–1735, Aug. 2012.

T. Rabl, **M. Sadoghi**, K. Zhang, and H. Jacobsen.
Poster: MADES - a multi-layered, adaptive, distributed event store.
In S. Chakravarthy, S. D. Urban, P. Pietzuch, and E. A. Rundensteiner, editors, *The 7th ACM International Conference on Distributed Event-Based Systems, DEBS 2013, Arlington, TX, USA - June 29 - July 03, 2013*, pages 343–344. ACM, 2013.

T. Rabl, K. Zhang, **M. Sadoghi**, N. K. Pandey, A. Nigam, C. Wang, and H.-A. Jacobsen.
Solving manufacturing equipment monitoring through efficient complex event processing: Debs grand challenge.
In *Proceedings of the 6th ACM International Conference on Distributed Event-Based Systems*, DEBS 2012, pages 335–340, Berlin, Germany, 2012. ACM.

M. Sadoghi.
Towards an extensible efficient event processing kernel.
In *Proceedings of the SIGMOD/PODS 2012 PhD Symposium*, PhD 2012, pages 3–8, Scottsdale, Arizona, USA, 2012. ACM.

M. Sadoghi, I. Burcea, and H.-A. Jacobsen.
GPX-Matcher: a generic Boolean predicate-based XPath expression matcher.
In *Proceedings of the 14th International Conference on Extending Database Technology*, EDBT/ICDT 2011, pages 45–56, Uppsala, Sweden, 2011. ACM.

M. Sadoghi, M. Canim, B. Bhattacharjee, F. Nagel, and K. A. Ross.
Reducing database locking contention through multi-version concurrency.
PVLDB 2014, 7(13):1331–1342, 2014.

M. Sadoghi and H. Jacobsen.
Adaptive parallel compressed event matching.
In *IEEE 30th International Conference on Data Engineering, Chicago, ICDE 2014, IL, USA, March 31 - April 4, 2014*, pages 364–375, 2014.

M. Sadoghi and H.-A. Jacobsen.
BE-Tree: an index structure to efficiently match Boolean expressions over high-dimensional discrete space.
In *Proceedings of the 2011 ACM SIGMOD International Conference on Management of data*, SIGMOD 2011, pages 637–648, Athens, Greece, 2011. ACM.

M. Sadoghi and H.-A. Jacobsen.
Location-based matching in publish/subscribe revisited.
In *Proceedings of the Posters and Demo Track*, Middleware 2012, pages 9:1–9:2, Montreal, Quebec, Canada, 2012. ACM.

M. Sadoghi and H.-A. Jacobsen.
Relevance matters: Capitalizing on less (top-k matching in publish/subscribe).
In *IEEE 28th International Conference on Data Engineering*, ICDE 2012, pages 786–797, Arlington, Virginia, USA, 2012. IEEE Computer Society.

M. Sadoghi and H.-A. Jacobsen.
Analysis and optimization for Boolean expression indexing.
ACM Trans. Database Syst., TODS 2013, 38(2):8:1–8:47, July 2013.

M. Sadoghi, H.-A. Jacobsen, M. Labrecque, W. Shum, and H. Singh.
Efficient event processing through reconfigurable hardware for algorithmic trading.
Proceedings of the VLDB Endowment, PVLDB 2010, 3(2):1525–1528, 2010.

M. Sadoghi, R. Javed, N. Tarafdar, H. Singh, R. Palaniappan, and H.-A. Jacobsen.
Multi-query stream processing on fpgas.
In *Proceedings of the 2012 IEEE 28th International Conference on Data Engineering*, ICDE 2012, pages 1229–1232, Washington, DC, USA, 2012. IEEE Computer Society.

M. Sadoghi, M. Jergler, H.-A. Jacobsen, R. Hull, and R. Vaculin.
Safe distribution and parallel execution of data-centric workflows over the publish/subscribe abstraction.
IEEE Trans. on Knowl. and Data Eng., TKDE 2015, 2015.

M. Sadoghi, M. Jergler, H.-A. Jacobsen, R. Hull, and R. Vaculin.
Safe distribution and parallel execution of data-centric workflows over the publish/subscribe abstraction.
In *32nd IEEE International Conference on Data Engineering, ICDE 2016, Helsinki, Finland, May 16-20, 2016*, pages 1498–1499, 2016.

M. Sadoghi and N. Koudas.
SPIDER: Data Quality & Data Cleaning Project.
In the 15th International Conference of Center for Advanced Studies on Collaborative Research, IBM CASCON 2005. October 17-20, 2005. 2005.

M. Sadoghi, K. A. Ross, M. Canim, and B. Bhattacharjee.
Making updates disk-I/O friendly using SSDs.
PVLDB 2013, 6(11):997–1008, 2013.

M. Sadoghi, K. A. Ross, M. Canim, and B. Bhattacharjee.
Exploiting ssds in operational multiversion databases.
VLDB J., 25(5):651–672, 2016.

M. Sadoghi, S. Bhattacherjee, B. Bhattacharjee, and M. Canim.
L-Store: A real-time OLTP and OLAP system.
CoRR, abs/1601.04084, 2016.

M. Sadoghi, H. Singh, and H.-A. Jacobsen.
fpga-ToPSS: line-speed event processing on FPGAs.
In *Proceedings of the 5th ACM international conference on Distributed event-based system*, DEBS 2011, pages 373–374, New York, New York, USA, 2011. ACM.

M. Sadoghi, H. Singh, and H.-A. Jacobsen.
Towards highly parallel event processing through reconfigurable hardware.
In *Proceedings of the Seventh International Workshop on Data Management on New Hardware*, DaMoN 2011 at SIGMOD, pages 27–32, Athens, Greece, 2011. ACM.

M. Sadoghi.
ExpoDB: An Exploratory Data Science Platform.
In *Proceedings of the 8th Biennial Conference on Innovative Data Systems Research, CIDR 2017, Chaminade, CA, USA, January 8-11, 2017.*

M. Sadoghi, K. Srinivas, O. Hassanzadeh, Y-C. Chang, M. Canim, A. Fokoue, and Y A. Feldman.
Self-curating databases.
In *Proceedings of the 19th International Conference on Extending Database Technology, EDBT'16, Bordeaux, France, March 15-16, 2016.*, pages 467–472, 2016.

T. Nguyen, M. Rodriguez-Muro, O. Hassanzadeh, A. Massimiliano Gliozzo, **M. Sadoghi**.
Joint Learning of Local and Global Features for Entity Linking via Neural Networks.
In *Proceedings of the 26th International Conference on Computational Linguistics, COLING'16, Osaka, Japan, December 11-16, 2016*, pages 2310–2320, 2016.

K. Zhang, **M. Sadoghi**, V. Muthusamy, and H.-A. Jacobsen.
Distributed ranked data dissemination in social networks.
In *Proceedings of 33rd International Conference on Distributed Computing Systems*, ICDCS 2013, Washington, DC, USA, 2013. IEEE Computer Society.

K. Zhang, **M. Sadoghi**, and H.-A. Jacobsen.
DL-store: A distributed hybrid OLTP and OLAP data processing engine.
In *36th IEEE International Conference on Distributed Computing Systems, ICDCS 2016, Nara, Japan, June 27-30, 2016*, pages 769–770, 2016.

M. Najafi, K. Zhang, H.-A. Jacobsen, **M. Sadoghi**.
Hardware Acceleration Landscape for Distributed Real-time Analytics: Virtues and Limitations.
In *IEEE 37^{th} International Conference on Distributed Computing Systems (ICDCS 2017), Atlanta, GA, USA, 5-8 June, 2017*, pages 1938–1948, 2017.

K. Zhang, V. Muthusamy, **M. Sadoghi**, H.-A. Jacobsen.
Efficient Covering for Top-k Filtering in Content-Based Publish/Subscribe Systems.
In *IEEE 37^{th} International Conference on Distributed Computing Systems (ICDCS 2017), Atlanta, GA, USA, 5-8 June, 2017*, pages 2039–2044, 2017.

Ehab Abdelhamid, Mustafa Canim, Mohammad Sadoghi, Bishwaranjan Bhattacharjee, Yuan-Chi Chang, and Panos Kalnis.
Incremental frequent subgraph mining on large evolving graphs.
IEEE Trans. Knowl. Data Eng., 29(12):2710–2723, 2017.

Ehab Abdelhamid, Mustafa Canim, Mohammad Sadoghi, Bishwaranjan Bhattacharjee, Yuan-Chi Chang, and Panos Kalnis.
Incremental frequent subgraph mining on large evolving graphs.
2018.

Gonzalo I. Diaz, Achille Fokoue, and Mohammad Sadoghi.
Embeds: Scalable, ontology-aware graph embeddings.
In *Proceedings of the 21th International Conference on Extending Database Technology, EDBT 2018, Vienna, Austria, March 26-29, 2018.*, pages 433–436, 2018.

Jana Giceva and Mohammad Sadoghi.
Hybrid OLTP and OLAP.
In Sherif Sakr and Albert Zomaya, editors, *Encyclopedia of Big Data Technologies*, pages 1–11. Springer International Publishing, Cham, 2018.

Suyash Gupta and Mohammad Sadoghi.
Blockchain Transaction Processing.
In Sherif Sakr and Albert Zomaya, editors, *Encyclopedia of Big Data Technologies*, pages 1–11. Springer International Publishing, Cham, 2018.

Suyash Gupta and Mohammad Sadoghi.
Easycommit: A non-blocking two-phase commit protocol.
In *Proceedings of the 21th International Conference on Extending Database Technology, EDBT 2018, Vienna, Austria, March 26-29, 2018.*, pages 157–168, 2018.

Mohamed S. Hassan, Tatiana Kuznetsova, Hyun Chai Jeong, Walid G. Aref, and Mohammad Sadoghi.
Extending in-memory relational database engines with native graph support.
In *Proceedings of the 21th International Conference on Extending Database Technology, EDBT 2018, Vienna, Austria, March 26-29, 2018.*, pages 25–36, 2018.

Mohamed S. Hassan, Tatiana Kuznetsova, Hyun Chai Jeong, Walid G. Aref, and Mohammad Sadoghi.
Grfusion: Graphs as first-class citizens in main-memory relational database systems.
In *Proceedings of the 2018 International Conference on Management of Data, SIGMOD Conference 2018, Houston, TX, USA, June 10-15, 2018*, pages 1789–1792, 2018.

Mohammedreza Najafi, Mohammad Sadoghi, and Hans-Arno Jacobsen.
A scalable circular pipeline design for multi-way stream joins in hardware.
In *34th IEEE International Conference on Data Engineering, ICDE 2018, Paris, France, April 16-19, 2018*, 2018.

Mohammad Sadoghi, Souvik Bhattacherjee, Bishwaranjan Bhattacharjee, and Mustafa Canim.
L-store: A real-time OLTP and OLAP system.
In *Proceedings of the 21th International Conference on Extending Database Technology, EDBT 2018, Vienna, Austria, March 26-29, 2018.*, pages 540–551, 2018.

Kaiwen Zhang, Mohammad Sadoghi, Vinod Muthusamy, and Hans-Arno Jacobsen.
Efficient covering for top-k filtering in content-based publish/subscribe systems.
In *Proceedings of the 18th ACM/IFIP/USENIX Middleware Conference, Las Vegas, NV, USA, December 11 - 15, 2017*, pages 174–184, 2017.

T. Qadah and M. Sadoghi.
QueCC: A queue-oriented, control-free concurrency architecture.
In *Proceedings of the 19th ACM/IFIP/USENIX Middleware Conference, Rennes, France, December 10 - 14, 2018*, 2018.