SCIENCE
PASSION
TECHNOLOGY

Architecture of DB Systems
11 Modern Concurrency Control

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Announcements/Org

- **#1 Video Recording**
  - Link in **TUbe** & **TeachCenter** (lectures will be public)
  - Optional attendance (independent of COVID)
  - **Virtual lectures** (recorded) until end of the year
    https://tugraz.webex.com/meet/m.boehm

- **#2 Programming Projects**
  - Deadline Reminder: **Jan 21, 11.59pm**, submission in TeachCenter
  - Preliminary Perf Target: **#pcores/2** (see **03 Data Layouts and Bufferpools**)
  - Team size has impact on quality/effort threshold but not on score
  - https://mboehm7.github.io/teaching/ws2122_adbs/Project_Setup_v4.zip

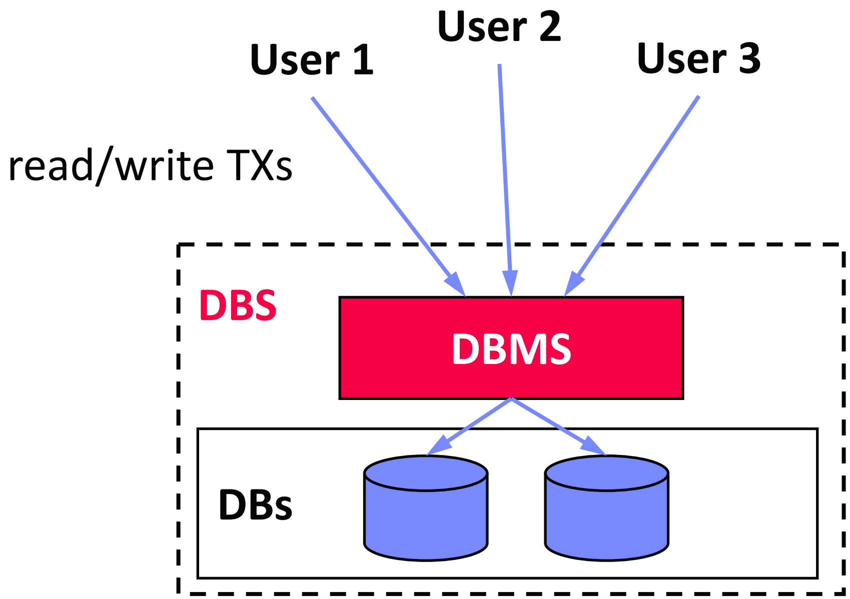
- **#3 Oral Exams**
  - **Oral exams, 45min** each, via
    https://tugraz.webex.com/meet/m.boehm
  - Exam Slots: Feb 7/8, Feb 24/25
    https://doodle.com/poll/zqiat5svr4xng7g4

Agenda

- **TX Processing Background**
- **Pessimistic and Optimistic Concurrency Control**
- **Multi-Version Concurrency Control**
- **Excursus: Coordination Avoidance**

TX Processing Background

Transaction (TX) Processing



#1 **Multiple users**
➔ **Correctness?**

#2 **Various failures**
(TX, system, media)
➔ **Reliability?**

Deadlocks

Constraint violations

Network failure

Crash/power failure

Disk failure

- **Goal: Transaction Processing**
  - **#1** Locking and concurrency control to ensure **#1 correctness**
  - **#2** Logging and recovery to ensure **#2 reliability**

Terminology of Transactions

- **Database Transaction**
  - A transaction (TX) is a **series of steps** that brings a database from a **consistent state** into another (not necessarily different) **consistent state**
  - **ACID properties** (atomicity, consistency, isolation, durability)

- **Terminology by Example**

#2 Start/**begin of TX** (BOT/BT)

#1 Isolation level (defined by addressed anomalies)

#3 Reads and writes of data objects

#4 Abort/rollback TX (unsuccessful end of transaction, EOT/ET)

#5 Commit TX (successful end of transaction, EOT/ET)

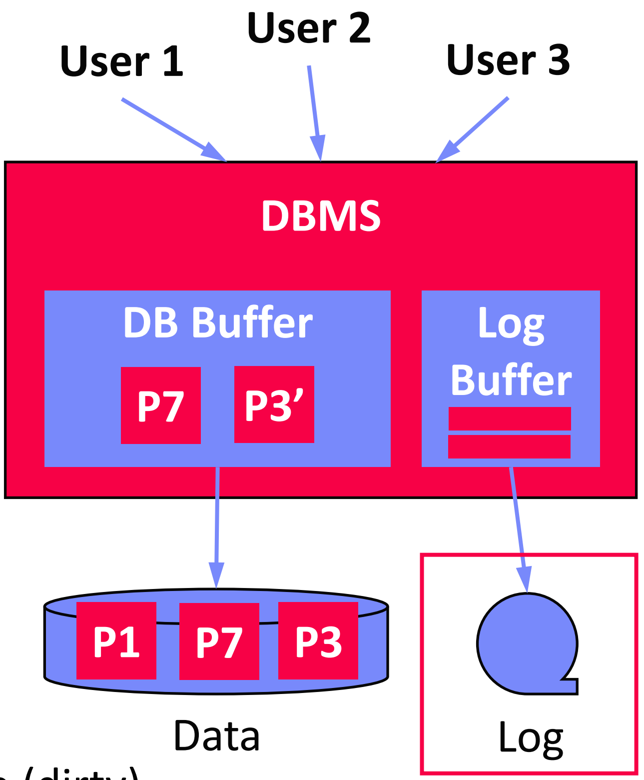
#6 Savepoints (checkpoint for partial rollback)

```
START TRANSACTION ISOLATION LEVEL SERIALIZABLE;
  UPDATE Account SET Balance=Balance-100
     WHERE AID = 107;
  UPDATE Account SET Balance=Balance+100
     WHERE AID = 999;

  SELECT Balance INTO lbalance
     FROM Account WHERE AID=107;
  IF lbalance < 0 THEN
     ROLLBACK TRANSACTION;
  END IF
COMMIT TRANSACTION;
```

Database (Transaction) Log

- **Database Architecture**
  - Page-oriented storage on disk and in memory (DB buffer)
  - Dedicated **eviction algorithms**
  - Modified in-memory pages marked as dirty, flushed by cleaner thread
  - Log: append-only TX changes
  - Data/log often placed on different devices and periodically archived (backup + truncate)



- **Write-Ahead Logging (WAL)**
  - The log records representing changes to some (dirty) data page must be on **stable storage before the data page** (UNDO - atomicity)
  - **Force-log on commit** or full buffer (REDO - durability)
  - **Recovery:** forward (REDO) and backward (UNDO) processing
  - Log sequence number (LSN)

[C. Mohan, Donald J. Haderle, Bruce G. Lindsay, Hamid Pirahesh, Peter M. Schwarz: ARIES: A Transaction Recovery Method Supporting Fine-Granularity Locking and Partial Rollbacks Using Write-Ahead Logging. **TODS 1992**]

Isolation Levels

- **Different Isolation Levels**
  - **Tradeoff Isolation vs performance** per session/TX
  - SQL standard requires **guarantee against lost updates** for all

```
SET TRANSACTION
    ISOLATION LEVEL
    READ COMMITTED
```

- **SQL Standard Isolation Levels**

Isolation Level	Lost Update	Dirty Read (P1)	Unrepeatable Read (P2)	Phantom Read (P3)
READ UNCOMMITTED	No*	Yes	Yes	Yes
READ COMMITTED	No*	No	Yes	Yes
REPEATABLE READ	No*	No	No	Yes
[SERIALIZABLE]	No*	No	No	No

* Lost update potentially w/ different semantics in standard

  - Serializable w/ highest guarantees (**pseudo-serial execution**)

- **How can we enforce these isolation levels?**
  - **User:** set default/transaction isolation level (mixed TX workloads possible)
  - **System:** dedicated concurrency control strategies + scheduler

Excursus: A Critique of SQL Isolation Levels

[Hal Berenson, Philip A. Bernstein, Jim Gray, Jim Melton, Elizabeth J. O'Neil, Patrick E. O'Neil: A Critique of ANSI SQL Isolation Levels. **SIGMOD 1995**]

- **Summary**
  - **Criticism:** SQL standard isolation levels are ambiguous (strict/broad interpretations)
  - Additional anomalies: dirty write, cursor lost update, fuzzy read, read skew, write skew
  - Additional isolation levels: **cursor stability** and **snapshot isolation**
- **Snapshot Isolation (< Serializable)**
  - **Type of optimistic concurrency control** via multi-version concurrency control
  - TXs reads data from a snapshot of committed data when TX started
  - **TXs never blocked on reads**, other TXs data invisible
  - TX **T1 only commits if no other TX wrote the same data items** in the time interval of T1
- **Current Status?**

  [http://dbmsmusings.blogspot.com/2019/05/introduction-to-transaction-isolation.html]

  - "SQL standard that **fails to accurately define database isolation levels** and database vendors that attach liberal and non-standard semantics"

Excursus: Isolation Levels in Practice

- **Default and Maximum Isolation Levels for "ACID" and "NewSQL" DBs [as of 2013]**
  - 3/18 `SERIALIZABLE` by default
  - 8/18 did not provide `SERIALIZABLE` at all

[Peter Bailis, Alan Fekete, Ali Ghodsi, Joseph M. Hellerstein, Ion Stoica: HAT, Not CAP: Towards Highly Available Transactions. **HotOS 2013**]

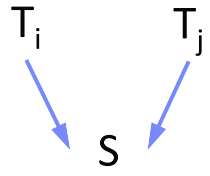
Beware of defaults, even though the SQL standard says **SERIALIZABLE** is the default

Database	Default	Maximum
Actian Ingres 10.0/10S [1]	S	S
Aerospike [2]	RC	RC
Akiban Persistit [3]	SI	SI
Clustrix CLX 4100 [4]	RR	RR
Greenplum 4.1 [8]	RC	S
IBM DB2 10 for z/OS [5]	CS	S
IBM Informix 11.50 [9]	Depends	S
MySQL 5.6 [12]	RR	S
MemSQL 1b [10]	RC	RC
MS SQL Server 2012 [11]	RC	S
NuoDB [13]	CR	CR
Oracle 11g [14]	RC	SI
Oracle Berkeley DB [7]	S	S
Oracle Berkeley DB JE [6]	RR	S
Postgres 9.2.2 [15]	RC	S
SAP HANA [16]	RC	SI
ScaleDB 1.02 [17]	RC	RC
VoltDB [18]	S	S

RC: read committed, RR: repeatable read, SI: snapshot isolation, S: serializability, CS: cursor stability, CR: consistent read

Serializability Theory

- **Operations of Transaction T_j**
  - **Read and write operations** of A by T_j: $r_j(A)$ $w_j(A)$
  - **Abort of transaction** T_j: a_j (unsuccessful termination of T_j)
  - **Commit of transaction** T_j: c_j (successful termination of T_j)
- **Schedule S**
  - Operations of a transaction **T_j are executed in order**
  - Multiple transactions may be executed concurrently
  - ➔ **Schedule describes the total ordering of operations**



- **Equivalence of Schedules S1 and S2**
  - Read-write, write-read, and write-write dependencies on data object A executed in same order:

$$r_i(A) <_{S1} w_j(A) \Leftrightarrow r_i(A) <_{S2} w_j(A)$$
$$w_i(A) <_{S1} r_j(A) \Leftrightarrow w_i(A) <_{S2} r_j(A)$$
$$w_i(A) <_{S1} w_j(A) \Leftrightarrow w_i(A) <_{S2} w_j(A)$$

Serializability Theory, cont.

- **Example Serializable Schedules**
  - Input TXs — T1: BOT $r_1(A)$ $w_1(A)$ $r_1(B)$ $w_1(B)$ c_1
    T2: BOT $r_2(C)$ $w_2(C)$ $r_2(A)$ $w_2(A)$ c_2
  - Serial execution: $r_1(A)$ $w_1(A)$ $r_1(B)$ $w_1(B)$ c_1 $r_2(C)$ $w_2(C)$ $r_2(A)$ $w_2(A)$ c_2
  - Equivalent schedules:
    $r_1(A)$ $r_2(C)$ $w_1(A)$ $w_2(C)$ $r_1(B)$ $r_2(A)$ $w_1(B)$ $w_2(A)$ c_1 c_2
    $r_1(A)$ $w_1(A)$ $r_2(C)$ $w_2(C)$ $r_1(B)$ $w_1(B)$ $r_2(A)$ $w_2(A)$ c_1 c_2
  - Wrong schedule: $r_1(A)$ $r_2(C)$ $w_2(C)$ $r_2(A)$ $w_1(A)$ $r_1(B)$ $w_1(B)$ $w_2(A)$ c_1 c_2
- **Serializability Graph (conflict graph)**
  - Operation dependencies (read-write, write-read, write-write) aggregated
  - **Nodes:** transactions; **edges:** transaction dependencies
  - **Transactions are serializable** (via topological sort) **if the graph is acyclic**
  - **Beware:** Serializability Theory considers only successful transactions, which disregards anomalies like dirty read that might happen in practice

Pessimistic and Optimistic Concurrency Control

Overview Concurrency Control

- **Terminology**
  - **Lock:** logical synchronization of TXs access to database objects (row, table, etc)
  - **Latch:** physical synchronization of access to shared data structures
- **#1 Pessimistic Concurrency Control**
  - Locking schemes (lock-based database scheduler)
  - Full serialization of transactions
- **#2 Optimistic Concurrency Control (OCC)**
  - Optimistic execution of operations, check of conflicts (validation)
  - Optimistic and timestamp-based database schedulers
- **#3 Mixed Concurrency Control (e.g., PostgreSQL)**
  - Combines locking and OCC
  - Might return **synchronization errors**

```
ERROR: could not serialize access
       due to concurrent update
ERROR: deadlock detected
```

Locking Schemes

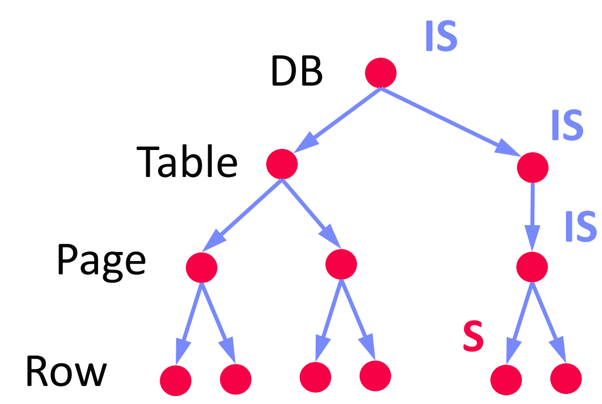
- **Compatibility of Locks**
  - X-Lock (exclusive/write lock)
  - S-Lock (shared/read lock)

Existing Lock (columns) / Requested Lock (rows)

	None	S	X
S	Yes	Yes	No
X	Yes	No	No

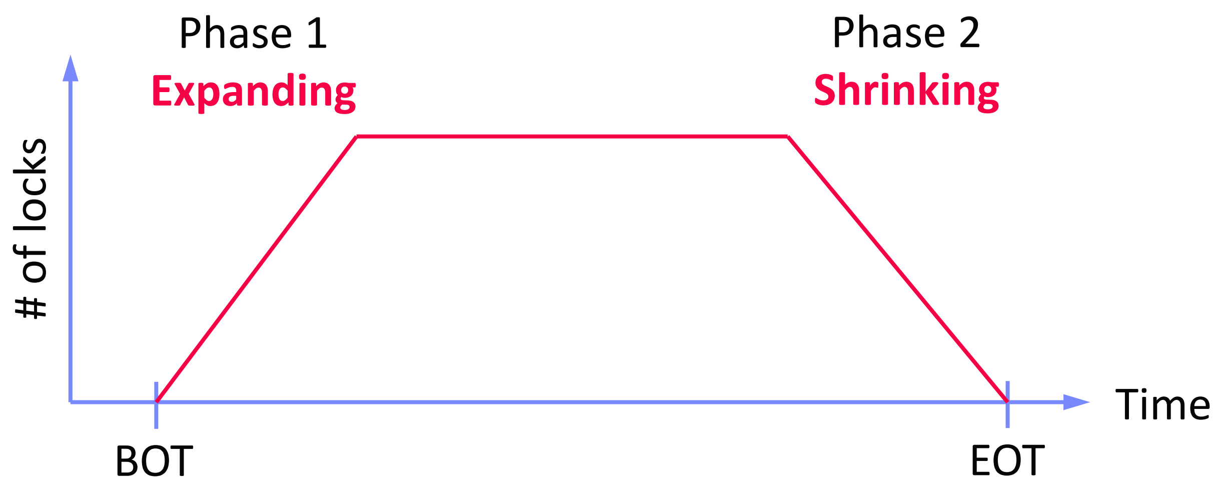
- **Multi-Granularity Locking**
  - Hierarchy of DB objects
  - Additional intentional IX and IS locks

	None	S	X	IS	IX
S	Yes	Yes	No	Yes	No
X	Yes	No	No	No	No
IS	Yes	Yes	No	Yes	Yes
IX	Yes	No	No	Yes	Yes



Two-Phase Locking (2PL)

- **Overview**
  - 2PL is a concurrency protocol that guarantees **SERIALIZABLE**
  - **Expanding phase** (growing): acquire locks needed by the TX
  - **Shrinking phase**: release locks acquired by the TX (can only start if all needed locks acquired)

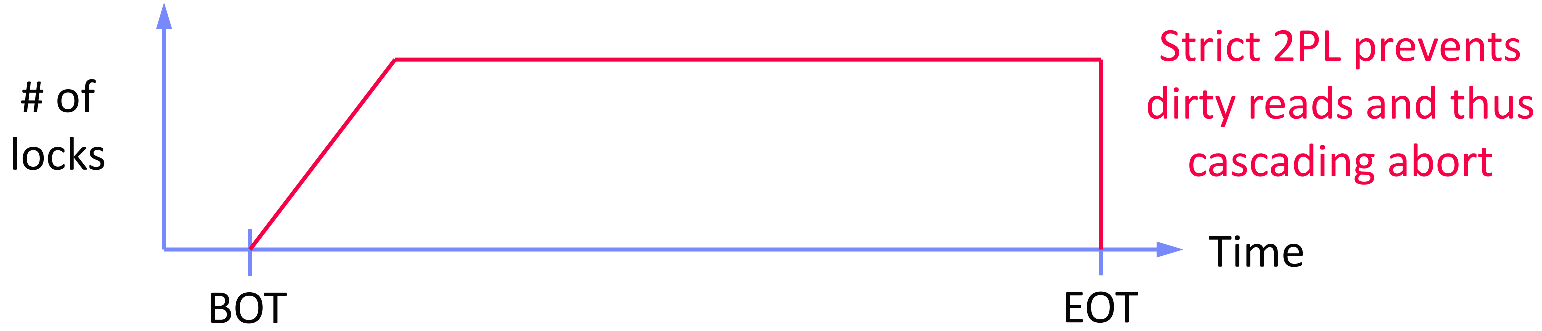


Dirty Read Problem

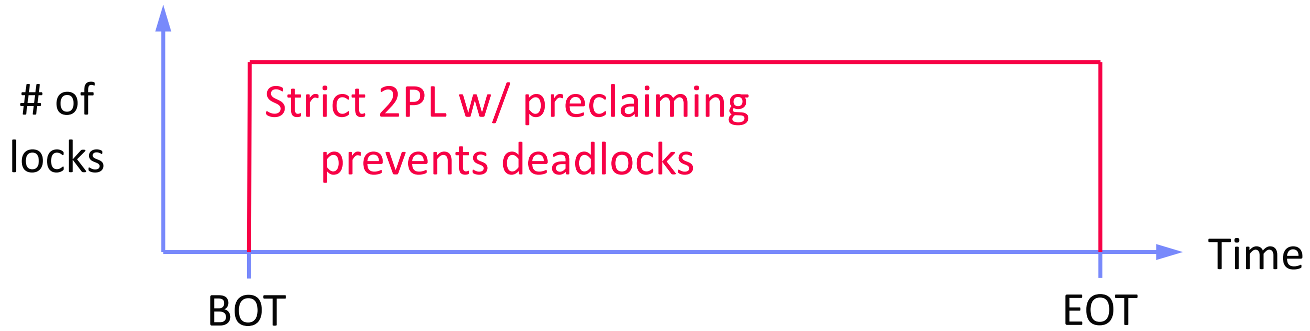
TX1	TX2
lock R	
lock S	
update R	
unlock R	
	lock R
	read R
abort	
	Dirty R

Two-Phase Locking, cont.

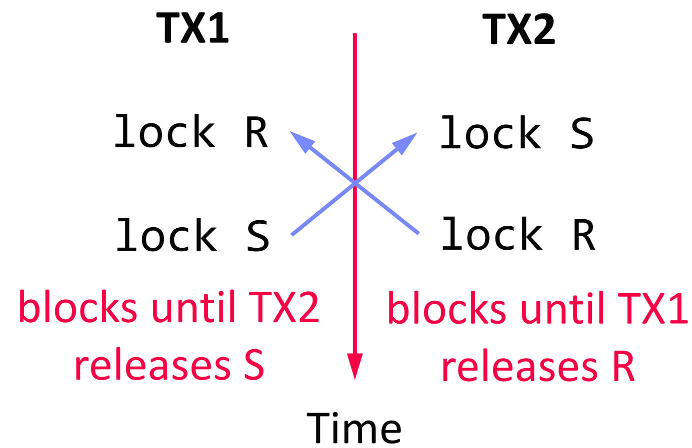
- **Strict 2PL (S2PL) and Strong Strict 2PL (SS2PL)**
  - **Problem:** Transaction rollback can cause (**Dirty Read**)
  - Release all X-locks (S2PL) or X/S-locks (SSPL) **at end of transaction (EOT)**



- **Strict 2PL w/ pre-claiming (aka conservative 2PL)**
  - Problem: incremental expanding can cause deadlocks for interleaved TXs
  - **Pre-claim all necessary locks** (only possible if entire TX known + **latches**)

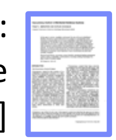


2PL – Deadlocks



DEADLOCK, as this will never happen

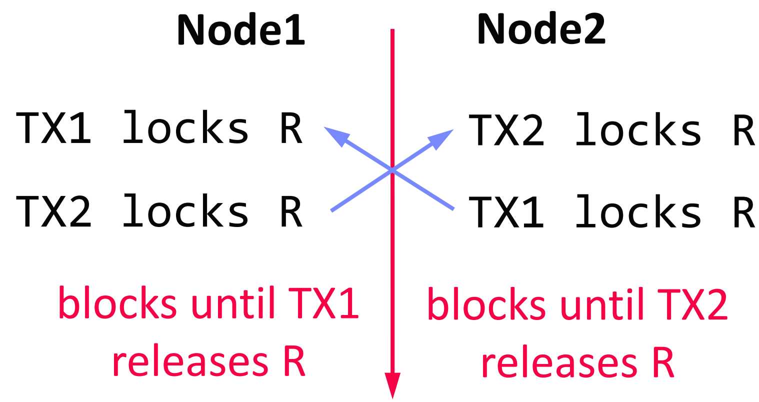
[Philip A. Bernstein, Nathan Goodman: Concurrency Control in Distributed Database Systems. **ACM Comput. Surv. 1981**]



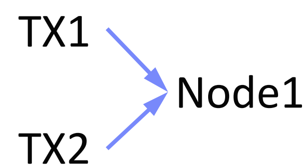
- **Deadlock Scenario**
  - Deadlocks of concurrent transactions
  - Deadlocks happen due to **cyclic dependencies without pre-claiming** (wait for exclusive locks)
- **#1 Deadlock Prevention**
  - Pre-claiming (guarantee if TX known upfront)
- **#2 Deadlock Avoidance**
  - Preemptive vs non-preemptive strategies
  - NO_WAIT (if deadlock suspected wrt timestamp TS, abort lock-requesting TX)
  - WOUND-WAIT (T1 locks something held by T2 → if T1<T2, restart T2)
  - WAIT-DIE (T1 locks something held by T2 → if T1>T2, abort T1 but keep TS)
- **#3 Deadlock Detection (DL_DETECT)**
  - Maintain a wait-for graph (WFG) of blocked TX (similar to serializability graph)
  - Detection of cycles in graph (on timeout) → abort one or many TXs

Excursus: Deadlocks in Distributed TXs

- **Deadlock Scenario**
  - Transmission delay
  - Distributed cyclic dependencies without pre-claiming (wait for exclusive locks)



- **#1 Deadlock Prevention**
  - **Pre-claiming** via a gatekeeper



- **#2 Deadlock Avoidance**
  - WOUND-DIE and WOUND-WAIT with broadcasting states
- **#3 Deadlock Detection**
  - **Centralized**: Build a global WFG from all local WFGs
  - **Hierarchical**: Cascade merge the local WFGs
  - **Distributed**: Detect deadlocks locally

[Elmagarmid A.K.: A Survey of Distributed Deadlock Detection Algorithms. **ACM SIGMOD Record 1986**]

[C. Mohan, B. Lindsay, R. Obermarck: Transaction Management in the R* Distribute Database Management System. **ACM Trans. Database Syst. 1986**]

Basic Timestamp Ordering (BTO)

[Philip A. Bernstein, Nathan Goodman: Concurrency Control in Distributed Database Systems. **ACM Comput. Surv. 1981**]

- **Synchronization Scheme**
  - Transactions get timestamp (or version) **TS(T_j)** at BOT
  - Each data object A has **readTS(A)** and **writeTS(A)**
  - Use timestamp comparison to validate access → serialized schedule
- **Read Protocol T_j(A)**
  - If TS(T_j) >= writeTS(A): **allow read**, set readTS(A) = max(TS(T_j), readTS(A))
  - If TS(T_j) < writeTS(A): **abort T_j** (older than last modifying TX)
- **Write Protocol T_j(A)**
  - If TS(T_j) >= readTS(A) & TS(T_j) >= writeTS(A): **allow write**, set writeTS(A)=TS(T_j)
  - If TS(T_j) < readTS(A): **abort T_j** (older than last reading TX)
  - If TS(T_j) < writeTS(A): **abort T_j** (older than last modifying TX)
- **BEWARE:** BTO requires handling of dirty reads, recoverability in general (e.g., via abort or versions)
  - Strict Timestamp Ordering (dirty bit) w/ deadlock avoidance techniques

[Stephan Wolf et al: An Evaluation of Strict Timestamp Ordering Concurrency Control for Main-Memory Database Systems. **IMDM@ VLDB 2013** (Revised Selected Papers)]

Excursus: BTO in Project WS20/21 Ref Impl

- **Overview TX Processing**
  - Implements variant of **basic timestamp ordering** (w/ handling of dirty reads)
  - **TX log for UNDO** of aborted transactions
  - **TIDs:** `__sync_fetch_and_add(&VAR,1)`

```
./speed_test 1468 0 0 0 0 \
              4000 160000 100
```

- **#1 Basic TO**
  - isReadable: TID >= WTS
  - IsWriteable: TID >= max(WTS, RTS)

```
NUM_TXN_FAIL: 0
NUM_TXN_COMP: 16,000,000
Time to run:  15.223s.
```

- **#2 Basic TO w/ Read Committed**
  - Basic TO w/ isReadable: TID >= WTS && !(TID != WTS && scanTXTable(ix, WTS))

```
NUM_TXN_FAIL: 0
NUM_TXN_COMP: 16,000,000
Time to run:  15.394s.
```

- **#3 Basic TO w/ Serializable**
  - Basic TO w/ read committed
  - Deleted bit, forced cleanup in epochs (∄ TS < max(RTS,WTS))

NotImplementedException

Optimistic Concurrency Control (OCC)

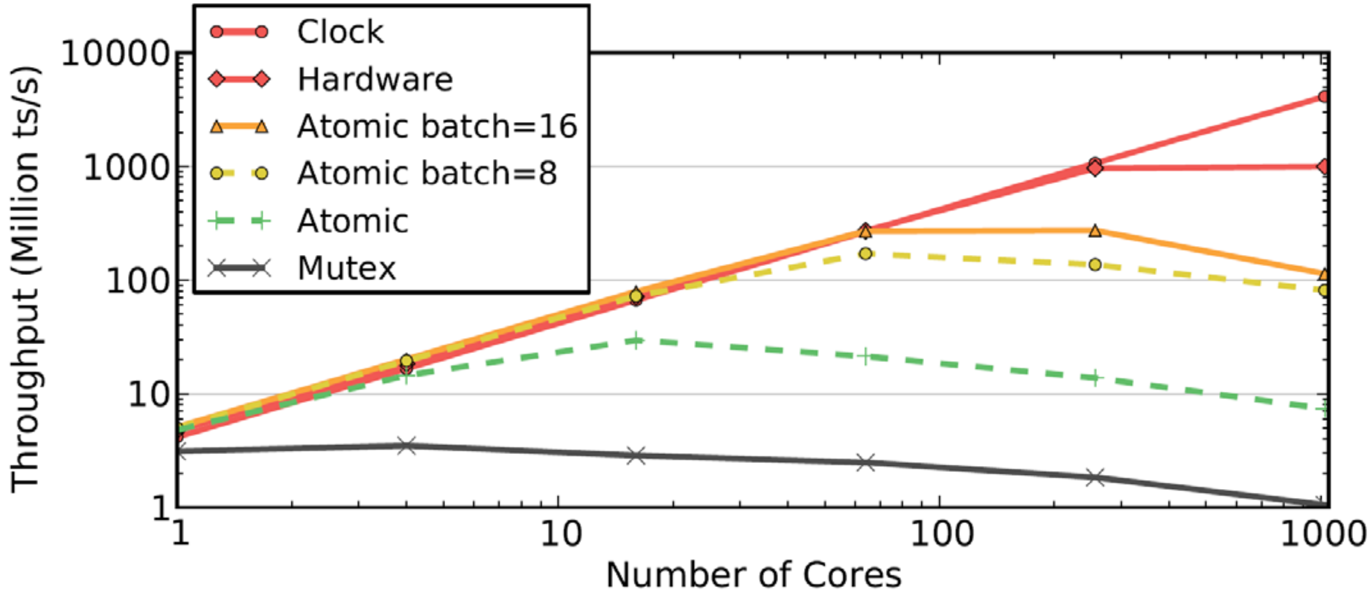
- **#1 Read Phase**
  - Initial reads from DB, **repeated reads and writes into TX-local buffer**
  - Maintain **ReadSet(T_j)** and **WriteSet(T_j)** per transaction T_j
  - TX seen as read-only transaction on database
- **#2 Validation Phase**
  - Check read/write and write/write conflicts, **abort on conflicts**
  - BOCC (Backward-oriented concurrency control) – check all older TXs T_i that finished (EOT) while T_j was running ($EOT(T_i) \geq BOT(T_j)$)
    - **Serializable:** if $EOT(T_i) < BOT(T_j)$ or $WSet(T_i) \cap RSet(T_j) = \emptyset$
    - **Snapshot isolation:** $EOT(T_i) < BOT(T_j)$ or $WSet(T_i) \cap WSet(T_j) = \emptyset$
  - FOCC (Forward-oriented concurrency control) – check running TXs
- **#3 Write Phase**
  - Successful TXs with write operations propagate their local buffer into the database and log

Timestamp Allocation

- **#1 Mutex**
- **#2 Atomic add / Batched Atomics**
- **#3 Decentralized / CPU Clock**
- **#4 Hardware** (CPU HW counter)

[Xiangyao Yu, George Bezerra, Andrew Pavlo, Srinivas Devadas, Michael Stonebraker: Staring into the Abyss: An Evaluation of Concurrency Control with One Thousand Cores. **PVLDB 8(3) 2014**]

[Stephen Tu, Wenting Zheng, Eddie Kohler, Barbara Liskov, Samuel Madden: Speedy transactions in multicore in-memory databases. **SOSP 2013**]

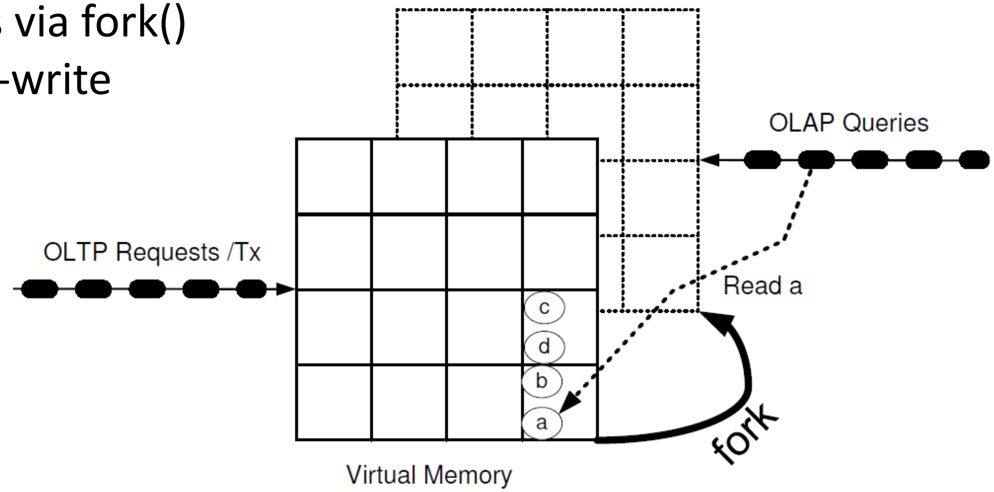


Multi-Version Concurrency Control (MVCC)

Snapshot Isolation w/ Snapshots

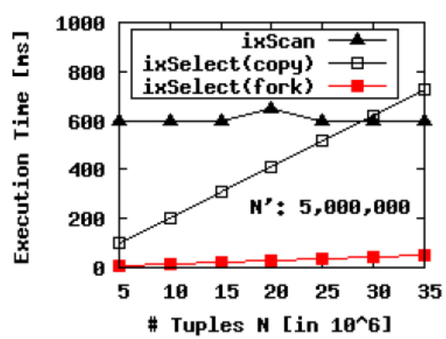
- **#1 Shadow Storage**
- **#2 Snapshots via Fork**
  - Partitioned, single-threaded OLTP ops
  - Snapshots via fork()
    + copy-on-write

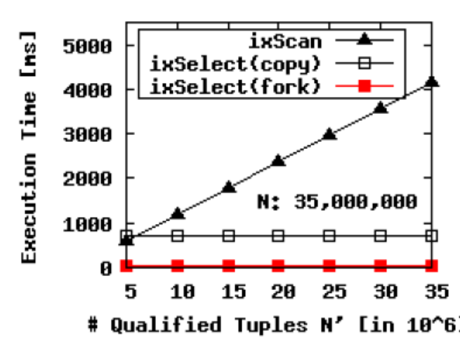
[Alfons Kemper, Thomas Neumann: HyPer: A hybrid OLTP&OLAP main memory database system based on virtual memory snapshots. **ICDE 2011**]



- **Excursus: Query Processing on Prefix Trees (via fork)**

[Matthias Boehm Patrick Lehmann Peter Benjamin Volk Wolfgang Lehner: Query Processing on Prefix Trees, **HPI Future SOC Lab 2011**]





MVCC Overview

- **MVCC Motivation**
  - Read TXs without need for locks, read sets, or copies (fine-grained management of individual versions)
  - Copy-on-write (readers never block writers), garbage collection when safe
  - Additional benefits: time travel, clear semantics, snapshot isolation
  - **Mixed HTAP workloads** → focus of many recent systems

- **Design Decisions**
  - **#1 Concurrency Control Protocol**
  - **#2 Version Storage**
    - Append-only, time-travel, delta
    - Oldest-to-newest/newest-to-oldest
  - **#3 Garbage Collection**
    - Tuple (background, coop), TX-level
  - **#4 Index Management**
    - Logical, physical pointers

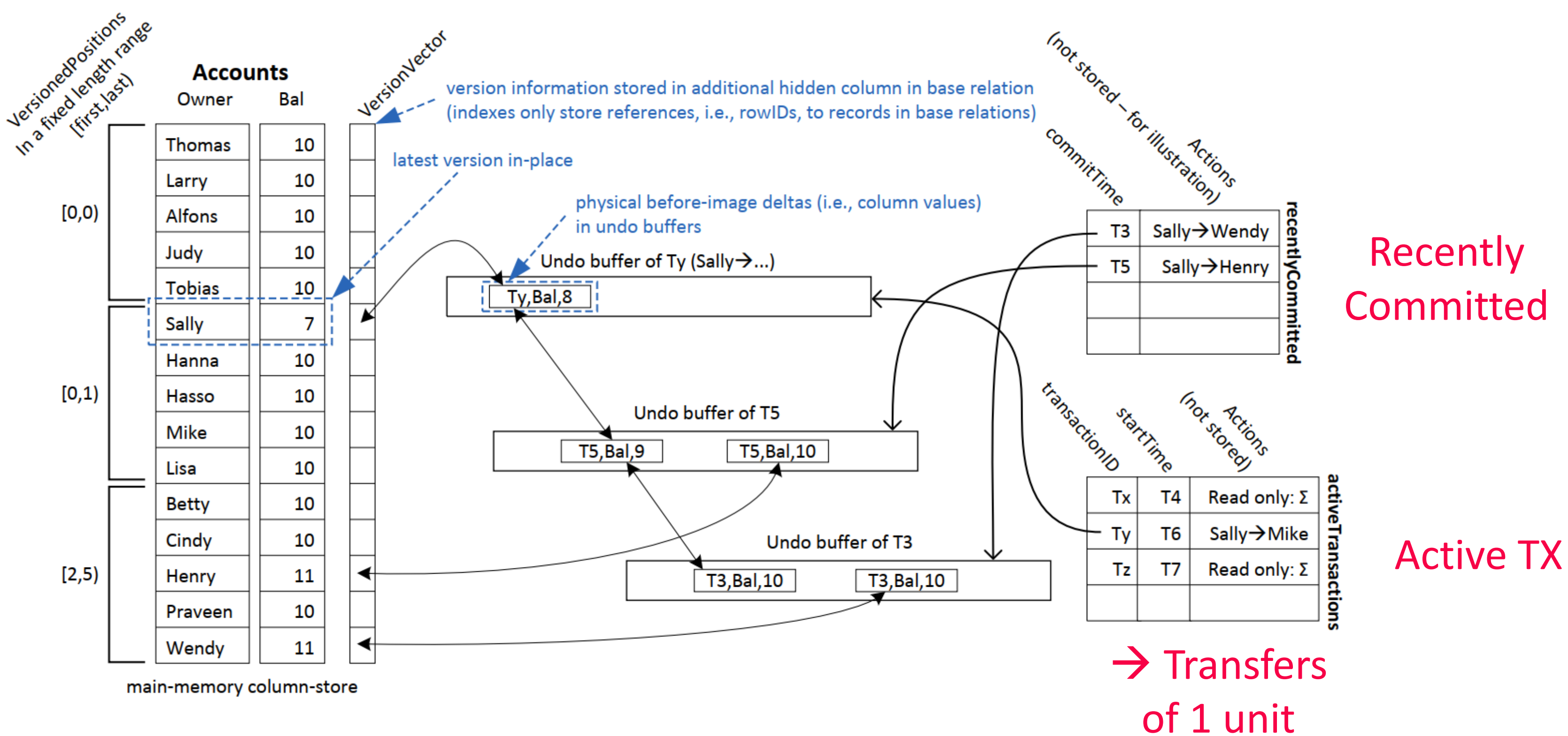
[Andy Pavlo: Advanced Database Systems – Multi-Version Concurrency Control (Design Decisions), **CMU 2020**]

[Yingjun Wu, Joy Arulraj, Jiexi Lin, Ran Xian, Andrew Pavlo: An Empirical Evaluation of In-Memory Multi-Version Concurrency Control. **PVLDB 10(7) 2017**]

Version Storage

[Thomas Neumann, Tobias Mühlbauer, Alfons Kemper: Fast Serializable Multi-Version Concurrency Control for Main-Memory Database Systems. **SIGMOD 2015**]

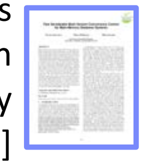
- **Example Hyper**
  - In-place update, backward delta in UNDO buffer
  - Almost no storage overhead (VersionVector), TX-local commit processing
  - Newest-to-oldest (preference for fast analytical queries)



Abort TX write-write conflicts on uncommitted changes

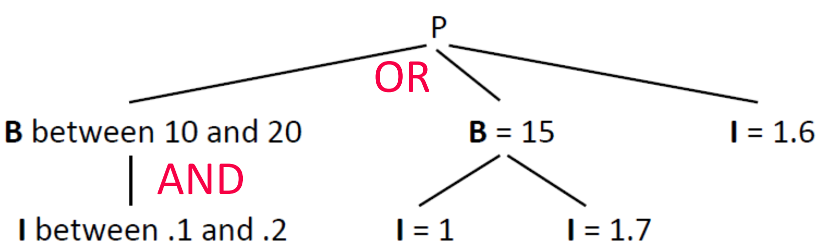
Serializability Validation

[Thomas Neumann, Tobias Mühlbauer, Alfons Kemper: Fast Serializable Multi-Version Concurrency Control for Main-Memory Database Systems. **SIGMOD 2015**]

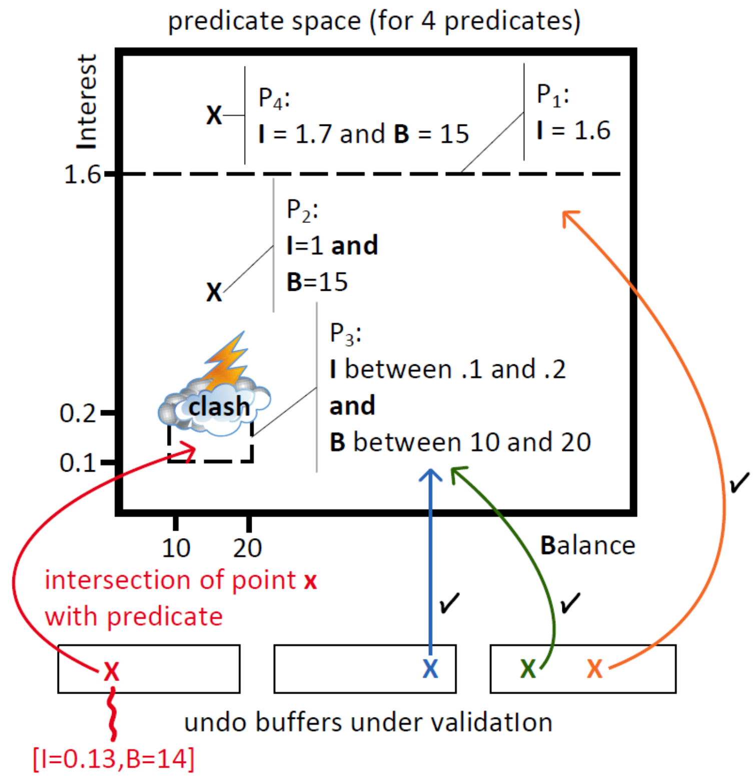


- **(Extended) Precision Locking**
  - **Predicate logging:** Instead of maintaining read-set, store read predicates of index and table scan of validated T_i in **predicate tree** (PT)
  - Recap: **Serializable:** if $EOT(T_i) < BOT(T_j)$ or $WSet(T_i) \cap RSet(T_j) = \emptyset$
  - Probe UNDO buffers (write set) of all T_j against predicate tree

Predicate Tree of T_i



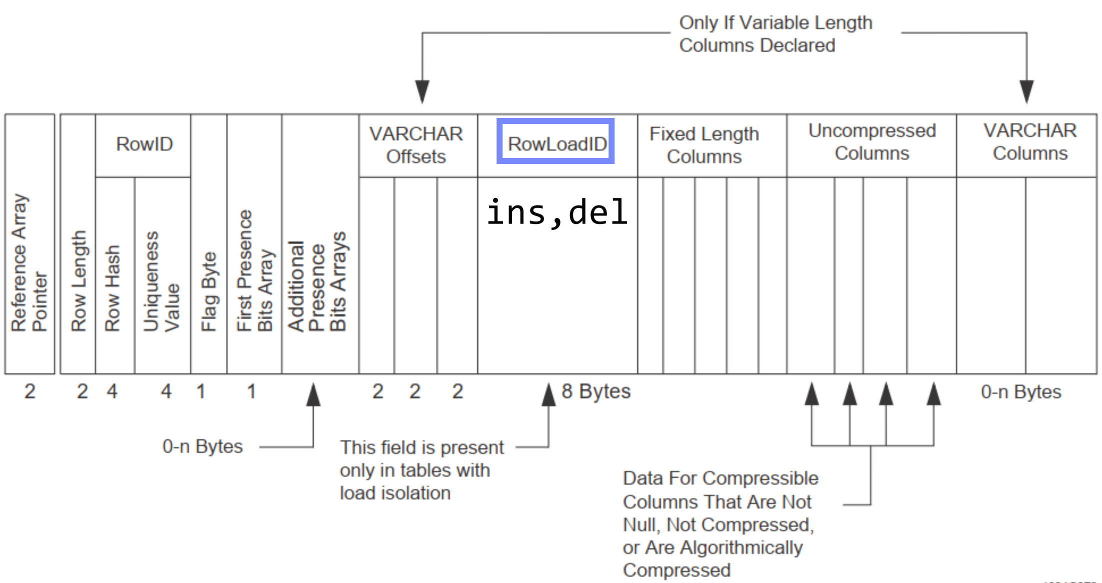
Abort Ti if a single UNDO buffer's data point matches



Excursus: Load Isolation in Teradata DB

- **Overview**
  - Single loader/writer, multiple readers
  - Writer session can select MVCC or Serializability
  - Append only version storage in the main table

[https://docs.teradata.com/r/w4DJnG9u9GdDlXzsTXyItA/S~gx1XKjg4ROKw2~8c01jQ]



Reader w/ ReadLoadID = 2

RLId	Cols
1,0	1,2,3
3,0	2,2,3
1,3	1,2,3

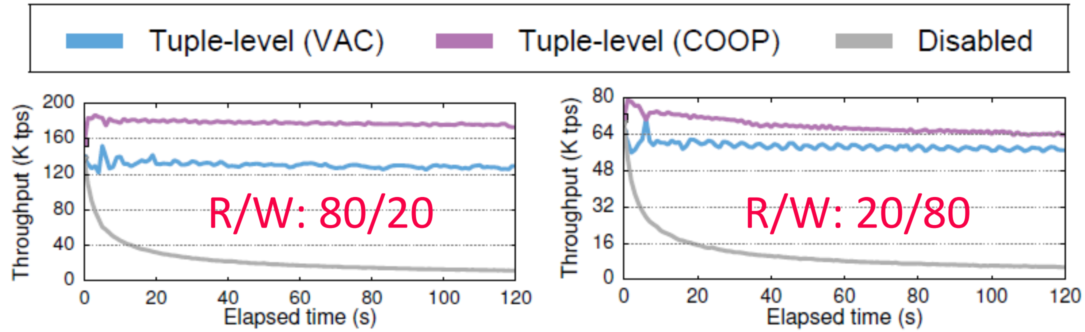
- Read condition (compiled as selection predicates)

```
ins_loaded <= ReadLoadID and del_loaded > ReadLoadID
```

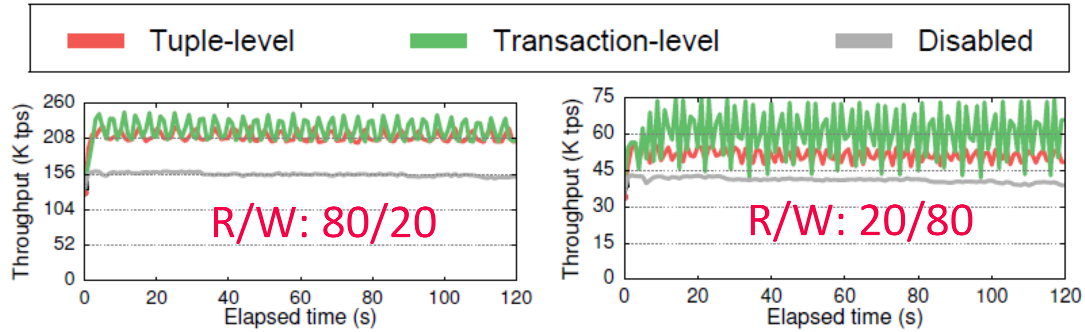
Garbage Collection

[Yingjun Wu, Joy Arulraj, Jiexi Lin, Ran Xian, Andrew Pavlo: An Empirical Evaluation of In-Memory Multi-Version Concurrency Control. **PVLDB 10(7) 2017**]

- **#1 Tuple-level Garbage Collection**
  - Background vacuuming
  - Cooperative cleaning on traversal)



- **#2 Transaction-level**
  - E.g., by epoch



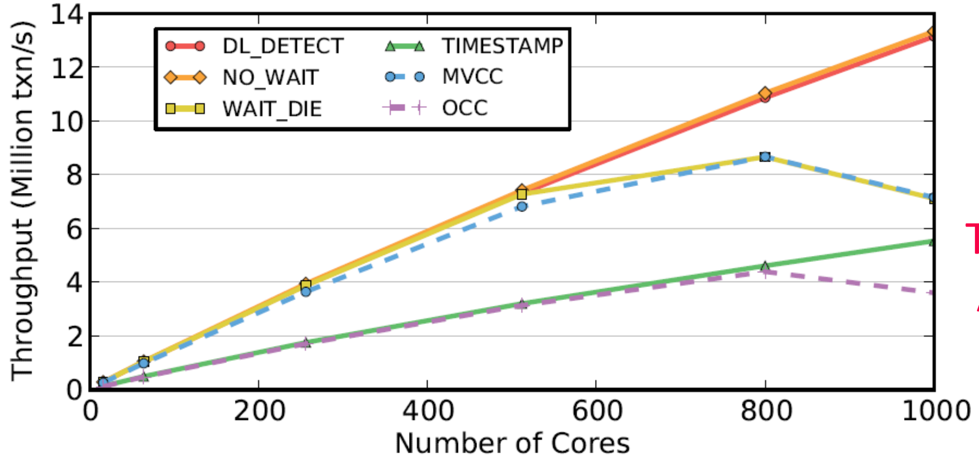
- **Deferred Action Framework (DAF)**
  - Maintenance tasks for GC, plan cache invalidation, data transformation

[Ling Zhang et al: Everything is a Transaction: Unifying Logical Concurrency Control and Physical Data Structure Maintenance in Database Management Systems, **CIDR 2021**]

Comparison (simulated)

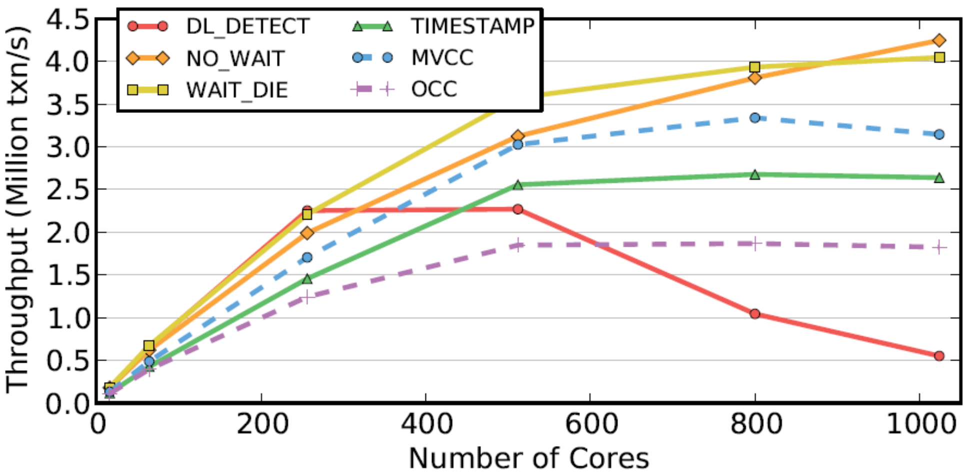
[Xiangyao Yu, George Bezerra, Andrew Pavlo, Srinivas Devadas, Michael Stonebraker: Staring into the Abyss: An Evaluation of Concurrency Control with One Thousand Cores. **PVLDB 8(3) 2014**]

- **Read-only Workload**



Timestamp Allocation

- **Write-intensive Workload** (medium contention)



Abort Rates

Lock Thrashing

Excursus: Coordination Avoidance

Overview Coordination Avoidance

- **Overview**
  - Ensure application-level invariants and convergence instead of (serializability vs weaker) with as little coordination as possible (different approaches)

With Transactions

[Peter Bailis, Ali Ghodsi, Joseph M. Hellerstein, Ion Stoica: Bolt-on causal consistency. **SIGMOD 2013**]

[Peter Bailis et al.: Coordination Avoidance in Database Systems. **PVLDB 8(3) 2014**]

[Peter Bailis: Coordination Avoidance in Distributed Databases. **PhD UC Berkeley 2015**]

Without Transactions

[Peter Alvaro, Neil Conway, Joseph M. Hellerstein, William R. Marczak: Consistency Analysis in Bloom: a CALM and Collected Approach. **CIDR 2011**]

[Peter Alvaro: Data-centric Programming for Distributed Systems. **PHD UC Berkeley 2015**]

[Chenggang Wu, Jose M. Faleiro, Yihan Lin, Joseph M. Hellerstein: Anna: A KVS for Any Scale. **ICDE 2018**]

[Chenggang Wu, Vikram Sreekanti, Joseph M. Hellerstein: Autoscaling Tiered Cloud Storage in Anna. **PVLDB 12(6) 2019**]

Summary and Q&A

- **TX Processing Background**
- **Pessimistic and Optimistic Concurrency Control**
- **Multi-Version Concurrency Control**
- **Excursus: Coordination Avoidance**

- **Next Lectures** (Part C)
  - **12 Modern Storage and HW Accelerators** [Jan 26]