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Carnegie Mellon Univ. Dept. of Computer Science 15-415/615 - DB Applications

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Lecture#23: Concurrency Control – Part 3

(R&G ch. 17)

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Last Class

- Lock Granularities
- Locking in B+Trees
- The Phantom Problem
- Transaction Isolation Levels

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Concurrency Control Approaches

- **Two-Phase Locking (2PL)**
  - Determine serializability order of conflicting operations at runtime while txns execute.
- **Timestamp Ordering (T/O)**
  - Determine serializability order of txns before they execute.

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Today's Class

- Basic Timestamp Ordering
- Optimistic Concurrency Control
- Multi-Version Concurrency Control
- Multi-Version+2PL
- Partition-based T/O
- Performance Comparisons

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Timestamp Allocation

- Each txn Ti is assigned a unique fixed timestamp that is monotonically increasing.
  - Let **TS(Ti)** be the timestamp allocated to txn Ti
  - Different schemes assign timestamps at different times during the txn.
- Multiple implementation strategies:
  - System Clock.
  - Logical Counter.
  - Hybrid.

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T/O Concurrency Control

- Use these timestamps to determine the serializability order.
- If **TS(**Ti**)** < **TS(**Tj**)**, then the DBMS must ensure that the execution schedule is equivalent to a serial schedule where Ti appears before Tj.

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Basic T/O

- Txns read and write objects without locks.
- Every object X is tagged with timestamp of the last txn that successfully did read/write:
  - **W-TS(X)** – Write timestamp on X
  - **R-TS(X)** – Read timestamp on X
- Check timestamps for every operation:
  - If txn tries to access an object "from the future", it aborts and restarts.

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Basic T/O – Reads

- If **TS(Ti)** < **W-TS(X)**, this violates timestamp order of Ti w.r.t. writer of X.
  - Abort Ti and restart it (with same TS? why?)
- Else
  - Allow Ti to read X.
  - Update **R-TS(X)** to **max(R-TS(X), TS(Ti))**
  - Have to make a local copy of X to ensure repeatable reads for Ti.

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Basic T/O – Writes

- If **TS(Ti)** < **R-TS(X)** or **TS(Ti)** < **W-TS(X)**
  - Abort and restart Ti.
- Else
  - Allow Ti to write X and update **W-TS(X)**
  - Also have to make a local copy of X to ensure repeatable reads for Ti.

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Basic T/O – Example #1

TS(T1)=1 dul TS(T2)=2

TIME

T1	T2
BEGIN	
R(B)	
	BEGIN
	R(B)
	W(B)
R(A)	
	R(A)
	W(A)
COMMIT	COMMIT

Database

Object	R-TS	W-TS
A	2	2
B	2	2
-	-	-

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Basic T/O – Example #2

Schedule

TIME

T1	T2
BEGIN	
R(A)	
	BEGIN
	W(A)
	COMMIT
W(A)	

T1 cannot overwrite update by T2, so it has to abort+restart.

Database

Object	R-TS	W-TS
A	1	2
-	-	-
-		

Violation: **TS(T1) < W-TS(A)**

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Basic T/O – Thomas Write Rule

- If **TS(Ti)** < **R-TS(O)**
  - Abort and restart Ti.
- If **TS(Ti)** < **W-TS(O)**
  - **Thomas Write Rule:** Ignore the write and allow the txn to continue.
  - This violates timestamp order of Ti
- Else
  - Allow Ti to write O and update **W-TS(O)**

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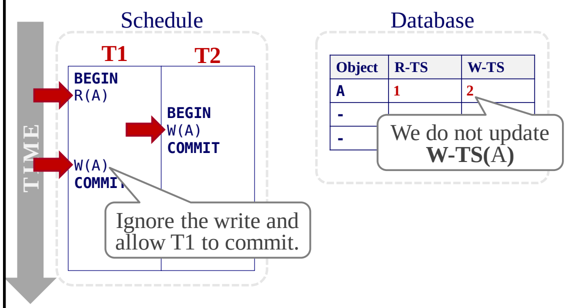
Basic T/O – Thomas Write Rule



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Basic T/O

- Ensures conflict serializability if you don't use the Thomas Write Rule.
- No deadlocks because no txn ever waits.
- Possibility of starvation for long txns if short txns keep causing conflicts.
- Permits schedules that are not ***recoverable***.

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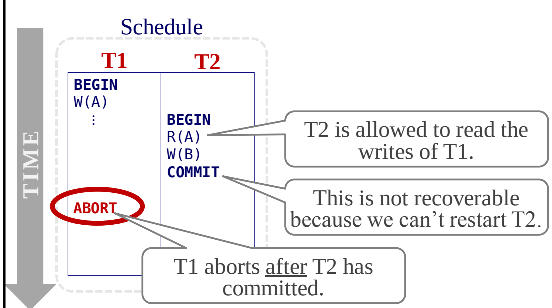
Recoverability



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Basic T/O – Performance Issues

- High overhead from copying data to txn's workspace and from updating timestamps.
- Long running txns can get starved.
- Suffers from timestamp bottleneck.

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Today's Class

- Basic Timestamp Ordering
- ➡ Optimistic Concurrency Control
- Multi-Version Concurrency Control
- Multi-Version+2PL
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Optimistic Concurrency Control

- Assumption: Conflicts are rare
- Forcing txns to wait to acquire locks adds a lot of overhead.
- Optimize for the no-conflict case.

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OCC Phases

- **Read:** Track the read/write sets of txns and store their writes in a private workspace.
- **Validation:** When a txn commits, check whether its *read set* overlaps with the *write set* of any concurrent txns.
- **Write:** If validation succeeds, apply private changes to database. Otherwise abort and restart the txn.

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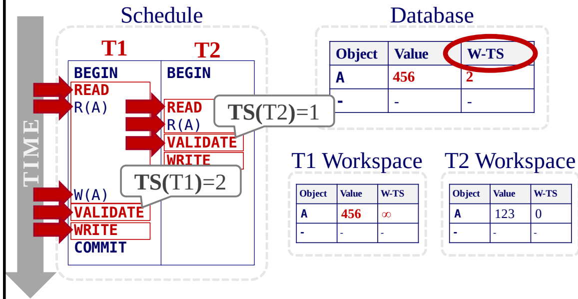
OCC – Example



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OCC – Validation Phase

- Need to guarantee only serializable schedules are permitted.
- At validation, Ti checks other txns for RW and WW conflicts and makes sure that all conflicts go one way (from older txns to younger txns).

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OCC – Validation Phase

- Each txn's timestamp is assigned at the beginning of the validation phase.
- Check the timestamp ordering of the committing txn with all other running txns.
- If **TS(**Ti**)** < **TS(**Tj**)**, then <u>one</u> of the following three conditions must hold…

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OCC – Validation #1

- Ti completes all three phases before Tj begins.

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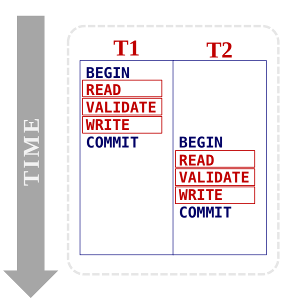
OCC – Validation #1



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OCC – Validation #2

- Ti completes before Tj starts its **Write** phase, and Ti does not write to any object read by Tj.
  - WriteSet(Ti) ∩ ReadSet(Tj) = Ø

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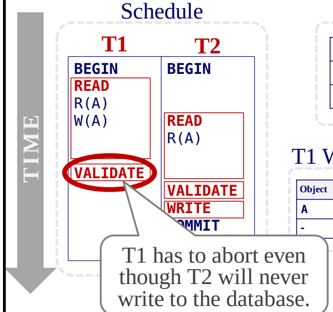
OCC – Validation #2



Database

Object	Value	W-TS
A	123	0
-	-	-

T1 Workspace

Object	Value	W-TS
A	456	∞
-	-	-

T2 Workspace

Object	Value	W-TS
A	123	0
-	-	-

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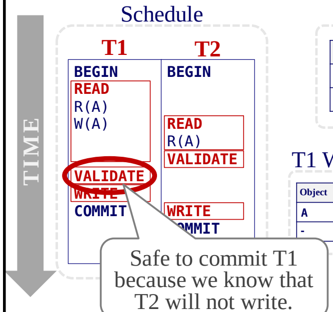
OCC – Validation #2



Database

Object	Value	W-TS
A	123	0
-	-	-

T1 Workspace

Object	Value	W-TS
A	456	∞
-	-	-

T2 Workspace

Object	Value	W-TS
A	123	0
-	-	-

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OCC – Validation #3

- Ti completes its **Read** phase before Tj completes its **Read** phase
- And Ti does not write to any object that is either read or written by Tj:
  - WriteSet(Ti) ∩ ReadSet(Tj) = Ø
  - WriteSet(Ti) ∩ WriteSet(Tj) = Ø

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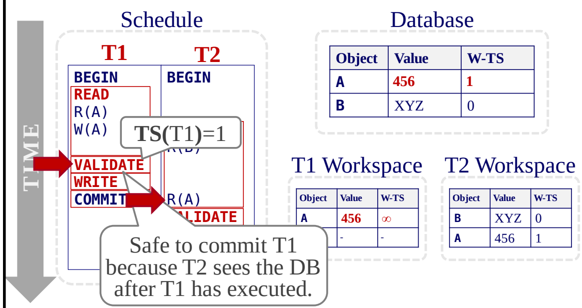
OCC – Validation #3



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OCC – Serial Validation

- Maintain global view of all active txns.
- Record read set and write set while txns are running and write into private workspace.
- Execute **Validation** and **Write** phase inside a protected critical section.

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OCC – Observations

- **Q:** When does OCC work well?
- **A:** When # of conflicts is low:
  - All txns are read-only (ideal).
  - Txns access disjoint subsets of data.
- If the database is large and the workload is not skewed, then there is a low probability of conflict, so again locking is wasteful.

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OCC – Performance Issues

- High overhead for copying data locally.
- **Validation/Write** phase bottlenecks.
- Aborts are more wasteful because they only occur *after* a txn has already executed.
- Suffers from timestamp allocation bottleneck.

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Multi-Version Concurrency Control

- Writes create new versions of objects instead of in-place updates:
  - Each successful write results in the creation of a new version of the data item written.
- Use write timestamps to label versions.
  - Let X_k denote the version of X where for a given txn Ti: **W-TS(**X_k**)** ≤ **TS(**Ti**)**

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MVCC – Reads

- Any read operation see the latest version of an object from right before that txn started.
- Every read request can be satisfied without blocking the txn.
- If **TS(**Ti**)** > **R-TS(**X_k**):**
  - Set **R-TS(**X_k**)** = **TS(**Ti**)**

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MVCC – Writes

- If **TS(**Ti**)** < **R-TS(**X_k**):**
  - Abort and restart Ti.
- If **TS(**Ti**)** = **W-TS(**X_k**):**
  - Overwrite the contents of X_k.
- Else
  - Create a new version of X_{k+1} and set its write timestamp to **TS(**Ti**)**.

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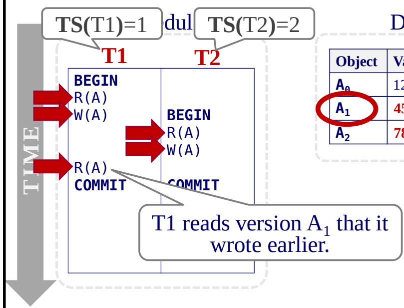
MVCC – Example #1



Database

Object	Value	R-TS	W-TS
A_0	123	1	0
A_1	456	2	1
A_2	789	2	2

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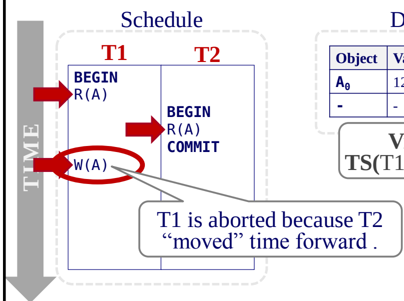
MVCC – Example #2



Database

Object	Value	R-TS	W-TS
A_0	123	2	0
-	-	-	

Violation: **TS**(T1) < **R-TS**(A_0)

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MVCC

- Can still incur cascading aborts because a txn sees uncommitted versions from txns that started before it did.
- Old versions of tuples accumulate.
- The DBMS needs a way to remove old versions to reclaim storage space.

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Garbage Collection – Postgres

- Never overwrites older versions.
- New tuples are appended to table.
- Deleted tuples are marked with a tombstone and then left in place.
- Separate background threads (**VACUUM**) has to scan tables to find tuples to remove.

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Garbage Collection – MySQL

- Only one "master" version for each tuple.
- Older versions are put into a temporary rollback segment and then pruned over time with a single thread (**PURGE**).
- Deleted tuples are left in place and the space is reused.

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MVCC – Performance Issues

- High abort overhead cost.
- Suffers from timestamp allocation bottleneck.
- Garbage collection overhead.
- Requires stalls to ensure recoverability.

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MVCC+2PL

- Combine the advantages of MVCC and 2PL together in a single scheme.
- Use different concurrency control scheme for read-only txns than for update txns.

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MVCC+2PL – Reads

- Use MVCC for read-only txns so that they never block on a writer
- Read-only txns are assigned a timestamp when they enter the system.
- Any read operations see the latest version of an object from right before that txn started.

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MVCC+2PL – Writes

- Use strict 2PL to schedule the operations of update txns:
  - Read-only txns are essentially ignored.
- Txns never overwrite objects:
  - Create a new copy for each write and set its timestamp to ∞.
  - Set the correct timestamp when txn commits.
  - Only one txn can commit at a time.

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MVCC+2PL – Performance Issues

- All the lock contention of 2PL.
- Suffers from timestamp allocation bottleneck.

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Observation

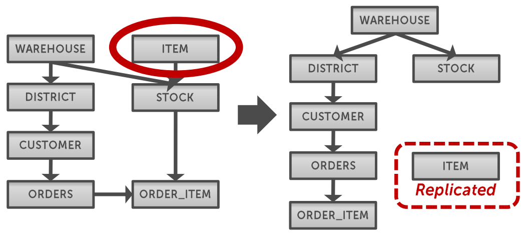
- When a txn commits, all previous T/O schemes check to see whether there is a conflict with concurrent txns.
- This requires locks/latches/mutexes.
- If you have a lot of concurrent txns, then this is slow even if the conflict rate is low.

Partition-based T/O

- Split the database up in disjoint subsets called *partitions* (aka *shards*).
- Only check for conflicts between txns that are running in the same partition.

Database Partitioning

Schema Schema Tree



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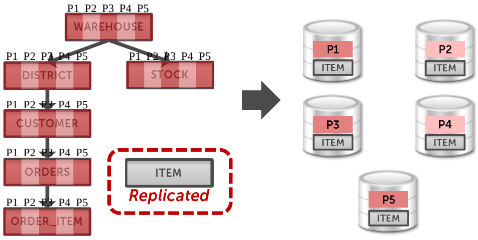
Database Partitioning

Schema Tree   Partitions



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Partition-based T/O

- Txns are assigned timestamps based on when they arrive at the DBMS.
- Partitions are protected by a single lock:
  – Each txn is queued at the partitions it needs.
  – The txn acquires a partition’s lock if it has the lowest timestamp in that partition’s queue.
  – The txn starts when it has all of the locks for all the partitions that it will read/write.

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Partition-based T/O – Reads

- Do not need to maintain multiple versions.
- Txns can read anything that they want at the partitions that they have locked.
- If a txn tries to access a partition that it does not have the lock, it is aborted + restarted.

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Partition-based T/O – Writes

- All updates occur in place.
  - Maintain a separate in-memory buffer to undo changes if the txn aborts.
- If a txn tries to access a partition that it does not have the lock, it is aborted + restarted.

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Partition-based T/O – Performance Issues

- Partition-based T/O protocol is very fast if:
  - The DBMS knows what partitions the txn needs before it starts.
  - Most (if not all) txns only need to access a single partition.
- Multi-partition txns causes partitions to be idle while txn executes.

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Performance Comparison

- Different schemes make different trade-offs.
- Measure how well each scheme scales on future many-core CPUs.
  - Ignore indexing and logging issues (for now).

Joint work with Xiangyao Yu, George Bezerra, Mike Stonebraker, and Srini Devadas.

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Graphite CPU Simulator

- Simulates a single CPU with 1024 cores.
  - Runs on a 22-node cluster.
  - Average slowdown: 10,000x
- Custom, lightweight DBMS that supports pluggable concurrency control coordinator.

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Tested CC Schemes

2PL Schemes	`DL_DETECT`	2PL with Deadlock Detection
	`NO_WAIT`	2PL with Non-waiting Deadlock Prevention
	`WAIT_DIE`	2PL with Wait-Die Deadlock Prevention
T/O Schemes	`TIMESTAMP`	Basic T/O
	`OCC`	Optimistic Concurrency Control
	`MVCC`	Multi-Version Concurrency Control
	`H-STORE`	Partition-based T/O

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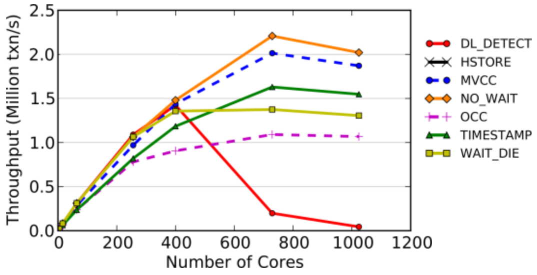
Benchmark #1

YCSB Workload – Read/Write (~60GB)



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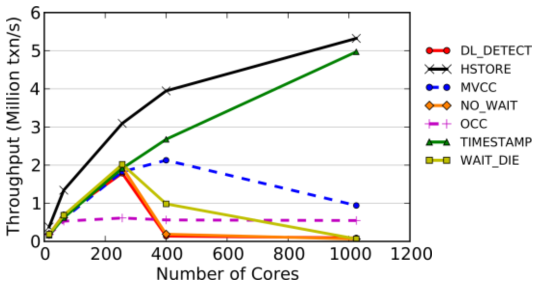
Benchmark #2

TPC-C Workload – 1024 Warehouses (~26GB)



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Which CC Scheme is Best?

- Like many things in life, it depends…
  - How skewed is the workload?
  - Are the txns short or long?
  - Is the workload mostly read-only?

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CC Schemes

2PL Schemes	DL_DETECT	Scales under low-contention. Suffers from lock thrashing and deadlocks.
	NO_WAIT	Has no centralized point of contention. Highly scalable. Very high abort rates.
	WAIT_DIE	Suffers from lock thrashing and timestamp allocation bottleneck. No deadlocks.
T/O Schemes	TIMESTAMP	High overhead from copying data and timestamp bottleneck. Non-blocking writes.
	OCC	Performs well for read-only workloads. Non-blocking reads and writes. Timestamp bottleneck.
	MVCC	High overhead for copying data locally. High abort cost. Suffers from timestamp bottleneck.
	H-STORE	The best algorithm for partitioned workloads. Suffers from timestamp bottleneck.

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Real Sysesms

	Scheme	Released
Ingres	Strict 2PL	1975
Informix	Strict 2PL	1980
IBM DB2	Strict 2PL	1983
Oracle	MVCC	1984*
Postgres	MVCC	1985
MS SQL Server	Strict 2PL	1992*
MySQL (InnoDB)	MVCC+2PL	2001
Aerospike	OCC	2009
SAP HANA	MVCC	2010
VoltDB	Partition T/O	2010
MemSQL	MVCC	2011
MS Hekaton	MVCC+OCC	2013

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Summary

- Concurrency control is hard.

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