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)

Last Class

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

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.

Today's Class

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

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.

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.

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.

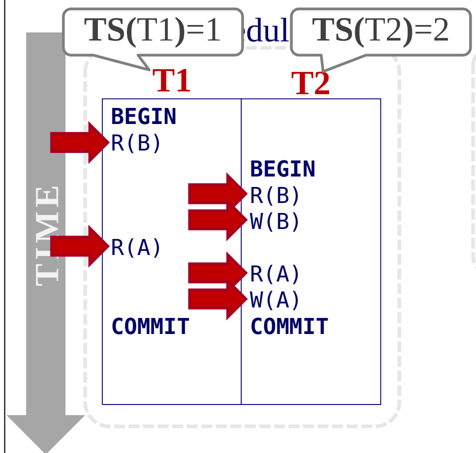
Basic T/O – Reads

- 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.

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.

Basic T/O – Example #1



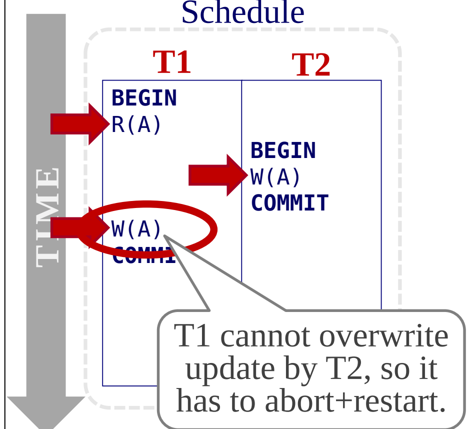
Database

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

No violations so both txns are safe to commit.

Basic T/O – Example #2

Schedule



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

Database

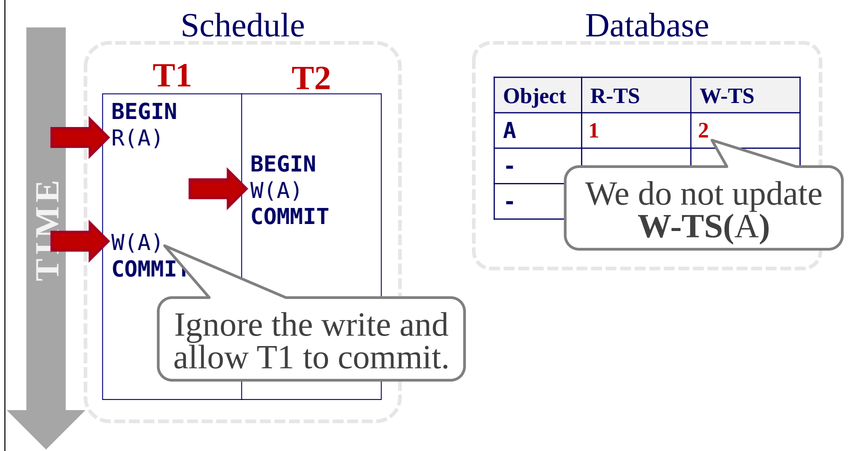
Object	R-TS	W-TS
A	1	2
-	-	-
-		

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

Basic T/O – Thomas Write Rule

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

Basic T/O – Thomas Write Rule



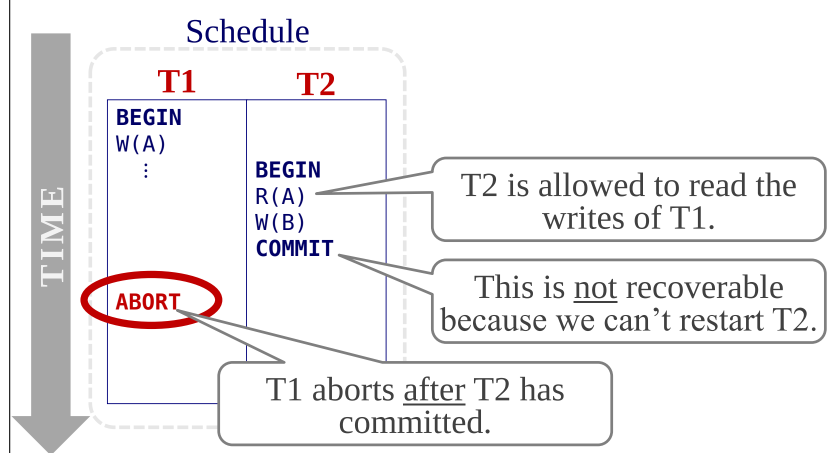
Basic T/O

- 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***.

Recoverable Schedules

- Transactions commit only after all transactions whose changes they read, commit.

Recoverability



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.

Today's Class

- Basic Timestamp Ordering
- Optimistic Concurrency Control
- Multi-Version Concurrency Control
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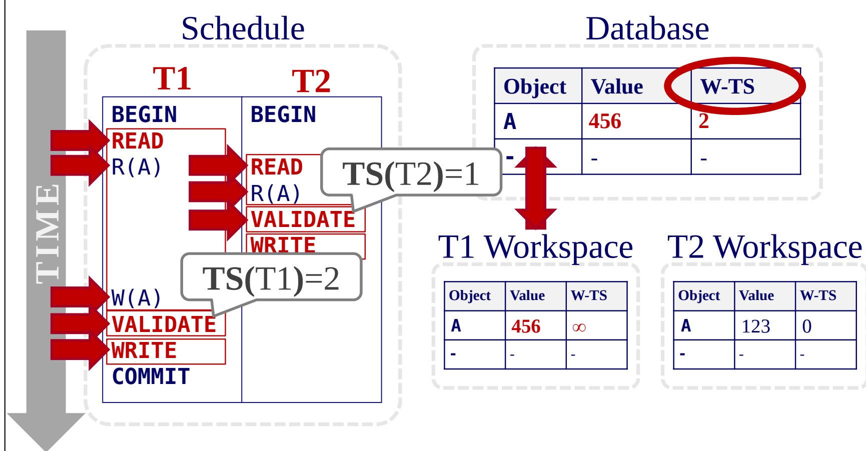
Optimistic Concurrency Control

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

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 it conflicts with other txns.
- **Write:** If validation succeeds, apply private changes to database. Otherwise abort and restart the txn.

OCC – Example



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).

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.

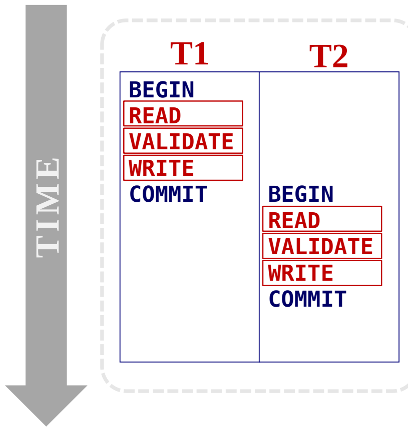
OCC – Validation Phase

- 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 one of the following three conditions must hold…

OCC – Validation #1

- Ti completes all three phases before Tj begins.

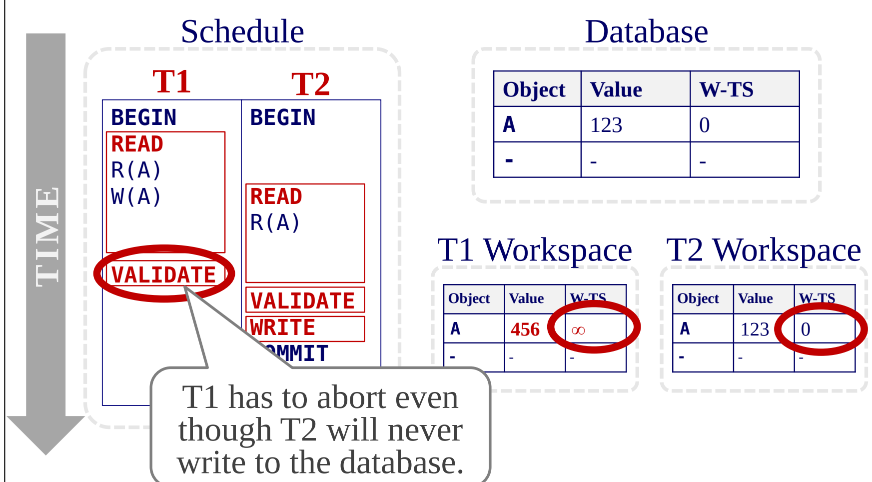
OCC – Validation #1



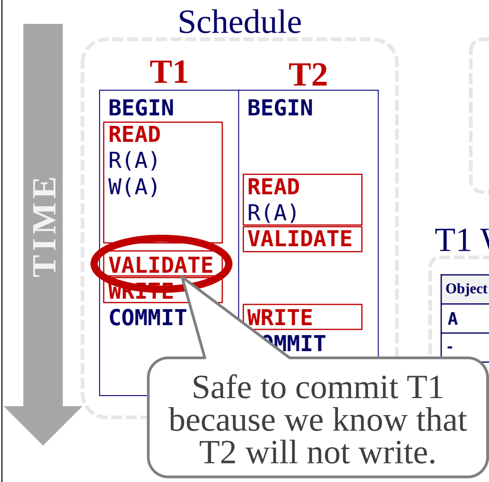
OCC – Validation #2

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

OCC – Validation #2



OCC – Validation #2



Database

Object	Value	W-TS
A	123	0
-	-	-

T1 Workspace

Object	Value	W-TS
A	456	∞
-	-	-

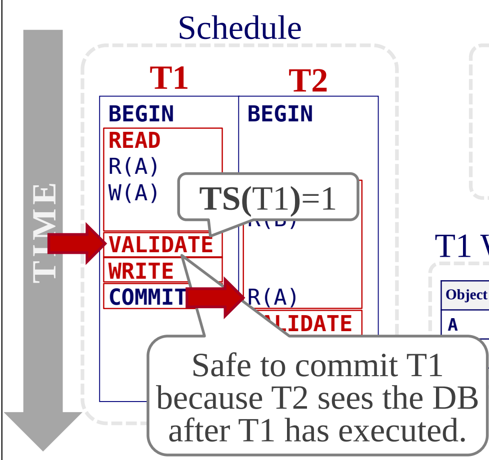
T2 Workspace

Object	Value	W-TS
A	123	0
-	-	-

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

OCC – Validation #3



Database

Object	Value	W-TS
A	456	1
B	XYZ	0

T1 Workspace

Object	Value	W-TS
A	456	∞
-	-	-

T2 Workspace

Object	Value	W-TS
B	XYZ	0
A	456	1

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.

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)

MVCC – Reads

- Any read operation sees 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)

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).

MVCC – Example #1

TS(T1)=1

TS(T2)=2

Schedule

TIME

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

T1 reads version A_1 that it wrote earlier.

Database

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

MVCC – Example #2

Schedule

TIME

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

T1 is aborted because T2 "moved" time forward .

Database

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

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

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.

MVCC Implementations

- Store versions directly in main tables:
  - Postgres, Firebird/Interbase
- Store versions in separate temp tables:
  - MSFT SQL Server
- Only store a single master version:
  - Oracle, MySQL

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.

Garbage Collection – MySQL

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

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.

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.

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.

MVCC+2PL – Performance Issues

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

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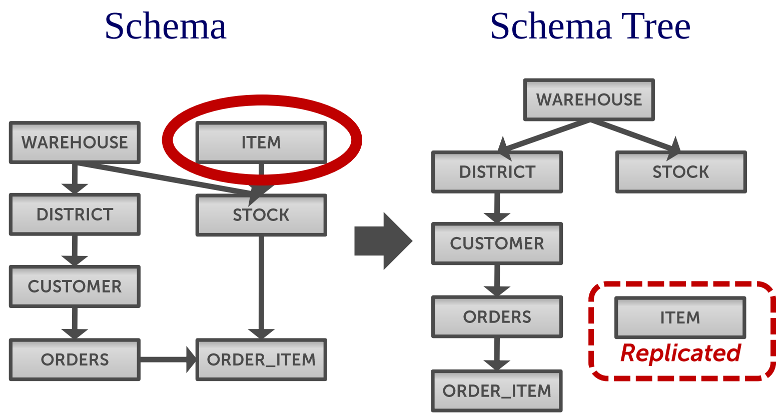
Observation

- 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.

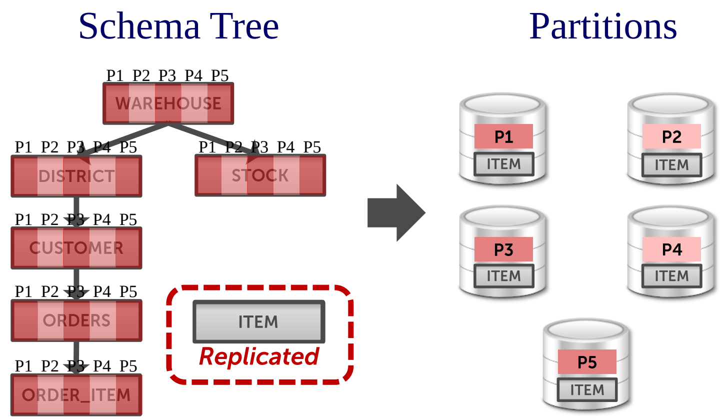
Partition-based T/O

- 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



Database Partitioning



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.

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.

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.

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.

http://cmudb.io/1000cores

Graphite CPU Simulator

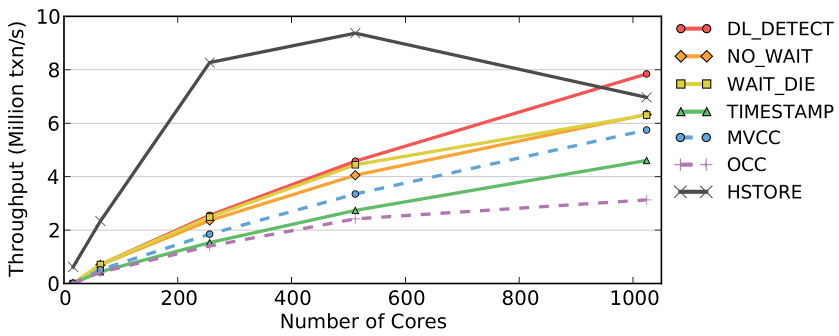
- Simulates a single CPU with 1024 cores.
  - Runs on a 22-node cluster.
  - Average slowdown: 10,000x
- Custom, lightweight DBMS that supports pluggable concurrency control coordinator.

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

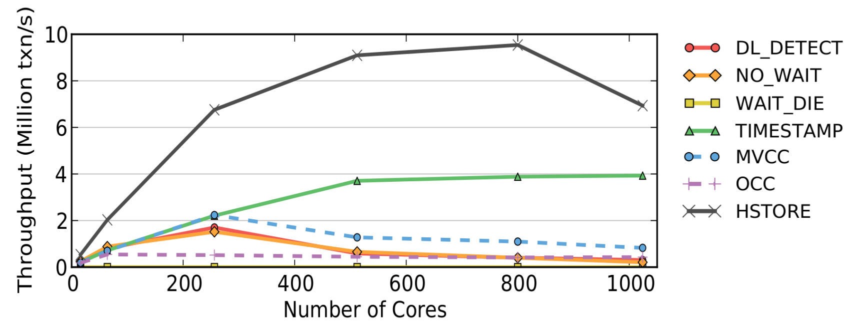
Benchmark #1

YCSB Workload – Read-Only (~60GB)



Benchmark #2

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



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?

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.

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 or MVCC	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

Summary

- Concurrency control is hard.