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 $\text{TS}(\text{Ti}) < \text{R-TS}(\text{X})$ or $\text{TS}(\text{Ti}) < \text{W-TS}(\text{X})$
  – Abort and restart Ti.

• Else:
  – Allow Ti to write X and update $\text{W-TS}(\text{X})$
  – Also have to make a local copy of X to ensure repeatable reads for Ti.

Basic T/O – Example #1

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

Schedule

Database

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

Violation: $\text{TS}(\text{T1}) < \text{W-TS}(\text{A})$

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

No violations so both txns are safe to commit.

Basic T/O – Example #2

Schedule

Database

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

Violation: $\text{TS}(\text{T1}) < \text{W-TS}(\text{A})$

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

Basic T/O – Thomas Write Rule

• If $\text{TS}(\text{Ti}) < \text{R-TS}(\text{X})$:
  – Abort and restart Ti.

• If $\text{TS}(\text{Ti}) < \text{W-TS}(\text{X})$:
  – 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 $\text{W-TS}(\text{X})$
Basic T/O – Thomas Write Rule

Schedule

T1

BEGIN
R(A)

T2

BEGIN
W(A)

COMMIT

Database

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

We do not update W-TS(A)

Ignore the write and allow T1 to commit.

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

Schedule

T1

BEGIN
W(A)

T2

BEGIN
R(A)

W(B)

COMMIT

T2 is allowed to read the writes of T1.

This is not recoverable because we can’t restart T2.

T1 aborts after T2 has committed.
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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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

Schedule

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1: BEGIN, READ R(A), VALIDATE W(A), COMMIT</td>
<td>T1 Workspace</td>
</tr>
<tr>
<td>T2: BEGIN, READ R(A), WRITE W(A)</td>
<td>T2 Workspace</td>
</tr>
</tbody>
</table>

```
Schedule       Database
             | Object | Value | W-TS
T1: BEGIN,    A      | 456    | 2     |
READ R(A),     -      | -      | -     |
VALIDATE W(A), -      | -      | -     |
COMMIT         -      | -      | -     |
T2: BEGIN,     A      | 123    | 0     |
READ R(A),     -      | -      | -     |
WRITE W(A)     -      | -      | -     |
```

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 #2

- Ti completes before Tj starts its Write phase, and Ti does not write to any object read by Tj.
  - $\text{WriteSet}(Ti) \cap \text{ReadSet}(Tj) = \emptyset$

T1 has to abort even though T2 will never write to the database.
OCC – Validation #2

- **Schedule**
  - T1: BEGIN READ R(A) VALIDATE WRITE COMMIT
  - T2: BEGIN READ R(A) VALIDATE WRITE COMMIT

- **Database**
  - Object | Value | W-TS
  - A | 123 | 0
  - A | - | -

- **T1 Workspace**
  - Object | Value | W-TS
  - A | 456 | ∞
  - A | 123 | 0

- **T2 Workspace**
  - Object | Value | W-TS
  - A | 123 | 0

- Safe to commit T1 because we know that T2 will not write.

OCC – Validation #3

- **Schedule**
  - T1: BEGIN READ R(A) VALIDATE WRITE COMMIT
  - T2: BEGIN READ R(B) R(A) VALIDATE WRITE COMMIT

- **Database**
  - Object | Value | W-TS
  - A | 123 | 0
  - B | XYZ | 0

- **T1 Workspace**
  - Object | Value | W-TS
  - A | 456 | ∞

- **T2 Workspace**
  - Object | Value | W-TS
  - A | 123 | 0
  - B | XYZ | 0
  - A | 456 | 1

- Safe to commit T1 because T2 sees the DB after T1 has executed.

- **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 – 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 $T_i$: $W-TS(X_k) \leq TS(T_i)$

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 $TS(T_i) > R-TS(X_k)$:
  - Set $R-TS(X_k) = TS(T_i)$
MVCC – Writes

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

MVCC – Example #1

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

<table>
<thead>
<tr>
<th>Object</th>
<th>Value</th>
<th>R-TS</th>
<th>W-TS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$</td>
<td>123</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$A_1$</td>
<td>456</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$A_2$</td>
<td>789</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

T1 reads version $A_1$ that it wrote earlier.

Violation: $\text{TS}(\text{Ti}) < \text{R-} \text{TS}(A_0)$

T1 is aborted because T2 “moved” time forward.

MVCC – Example #2

Schedule

Database

Violation: $\text{TS}(\text{Ti}) < \text{R-} \text{TS}(A_0)$

T1 is aborted because T2 “moved” time forward.

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 $\infty$.
  - 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

Partition-based T/O

- Txns are assigned timestamps based on when they arrive at the DBMS.
- Partitions are protected by a single lock:
  - Eachtxn 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 thetxn 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 Srinid 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

<table>
<thead>
<tr>
<th>T/O Schemes</th>
<th>2PL Schemes</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL_DETECT</td>
<td>2PL with Deadlock Detection</td>
</tr>
<tr>
<td>NO_WAIT</td>
<td>2PL with Non-waiting Deadlock Prevention</td>
</tr>
<tr>
<td>WAIT_DIE</td>
<td>2PL with Wait-Die Deadlock Prevention</td>
</tr>
<tr>
<td>TIMESTAMP</td>
<td>Basic T/O</td>
</tr>
<tr>
<td>OCC</td>
<td>Optimistic Concurrency Control</td>
</tr>
<tr>
<td>MVCC</td>
<td>Multi-Version Concurrency Control</td>
</tr>
<tr>
<td>H-STORE</td>
<td>Partition-based T/O</td>
</tr>
</tbody>
</table>

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**

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Released</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL_DETECT</td>
<td></td>
</tr>
<tr>
<td>NO_WAIT</td>
<td></td>
</tr>
<tr>
<td>WAIT_DIE</td>
<td></td>
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<tr>
<td>TIMESTAMP</td>
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</tr>
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<td>MVCC</td>
<td></td>
</tr>
<tr>
<td>H-STORE</td>
<td></td>
</tr>
</tbody>
</table>

**2PL Schemes**

- Scales under low-contention. Suffers from lock thrashing and deadlocks.
- Has no centralized point of contention. Highly scalable. Very high abort rates.
- Suffers from lock thrashing and timestamp allocation bottleneck. No deadlocks.
- High overhead from copying data and timestamp bottleneck. Non-blocking writes.
- Performs well for read-only workloads. Non-blocking reads and writes. Timestamp bottleneck.
- High overhead for copying data locally. High abort cost. Suffers from timestamp bottleneck.
- The best algorithm for partitioned workloads. Suffers from timestamp bottleneck.

**T/O Schemes**

- The best algorithm for partitioned workloads. Suffers from timestamp bottleneck.

**Real Systems**

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Released</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingres</td>
<td>1975</td>
</tr>
<tr>
<td>Informix</td>
<td>1980</td>
</tr>
<tr>
<td>IBM DB2</td>
<td>1983</td>
</tr>
<tr>
<td>Oracle</td>
<td>1984*</td>
</tr>
<tr>
<td>Postgres</td>
<td>1985</td>
</tr>
<tr>
<td>MS SQL Server</td>
<td>1992*</td>
</tr>
<tr>
<td>MySQL (InnoDB)</td>
<td>2001</td>
</tr>
<tr>
<td>Aerospike</td>
<td>2009</td>
</tr>
<tr>
<td>SAP HANA</td>
<td>2010</td>
</tr>
<tr>
<td>VoltDB</td>
<td>2010</td>
</tr>
<tr>
<td>MemSQL</td>
<td>2011</td>
</tr>
<tr>
<td>MS Hekaton</td>
<td>2013</td>
</tr>
</tbody>
</table>

**Summary**

- Concurrency control is hard.