Database Tuning
Concurrency Tuning

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Adapted from "Database Tuning" by Dennis Shasha and Philippe Bonnet.

Outline

1 Concurrency Tuning
- Introduction to Transactions
- Lock Tuning
- Weaken Isolation Guarantees
- Transaction Chopping

What is a Transaction?[1]

- A transaction is a unit of program execution that accesses and possibly updates various data items.
- Example: transfer \$50 from account A to account B
  1. $R(A)$
  2. $A \leftarrow A - 50$
  3. $W(A)$
  4. $R(B)$
  5. $B \leftarrow B + 50$
  6. $W(B)$
- Two main issues:
  1. concurrent execution of multiple transactions
  2. failures of various kind (e.g., hardware failure, system crash)

[1] Slides of section "Introduction to Transactions" are adapted from the slides "Database System Concepts", 6^{th} Ed., Silberschatz, Korth, and Sudarshan

ACID Properties

- Database system must guarantee ACID for transactions:
  - Atomicity: either all operations of the transaction are executed or none
  - Consistency: execution of a transaction in isolation preserves the consistency of the database
  - Isolation: although multiple transactions may execute concurrently, each transaction must be unaware of the other concurrent transactions.
  - Durability: After a transaction completes successfully, changes to the database persist even in case of system failure.

Atomicity

- Example: transfer \$50 from account A to account B
  1. $R(A)$
  2. $A \leftarrow A - 50$
  3. $W(A)$
  4. $R(B)$
  5. $B \leftarrow B + 50$
  6. $W(B)$
- What if failure (hardware or software) after step 3?
  - money is lost
  - database is inconsistent
- Atomicity:
  - either all operations or none
  - updates of partially executed transactions not reflected in database

Consistency

- Example: transfer \$50 from account A to account B
  1. $R(A)$
  2. $A \leftarrow A - 50$
  3. $W(A)$
  4. $R(B)$
  5. $B \leftarrow B + 50$
  6. $W(B)$
- Consistency in example: sum $A + B$ must be unchanged
- Consistency in general:
  - explicit integrity constraints (e.g., foreign key)
  - implicit integrity constraints (e.g., sum of all account balances of a bank branch must be equal to branch balance)
- Transaction:
  - must see consistent database
  - during transaction inconsistent state allowed
  - after completion database must be consistent again

Isolation – Motivating Example

- Example: transfer \$50 from account A to account B
  1. $R(A)$
  2. $A \leftarrow A - 50$
  3. $W(A)$
  4. $R(B)$
  5. $B \leftarrow B + 50$
  6. $W(B)$
- Imagine second transaction T_2:
  - $T_2 : R(A), R(B), print(A + B)$
  - T_2 is executed between steps 3 and 4
  - T_2 sees an inconsistent database and gives wrong result

Isolation

- Trivial isolation: run transactions serially
- Isolation for concurrent transactions: For every pair of transactions T_i and T_j, it appears to T_i as if either T_j finished execution before T_i started or T_j started execution after T_i finished.
- Schedule:
  - specifies the chronological order of a sequence of instructions from various transactions
  - equivalent schedules result in identical databases if they start with identical databases
- Serializable schedule:
  - equivalent to some serial schedule
  - serializable schedule of $T1$ and $T2$ is either equivalent to $T1, T2$ or $T2, T1$

Durability

- When a transaction is done it commits.
- Example: transaction commits too early
  - transaction writes A, then commits
  - A is written to the disk buffer
  - then system crashes
  - value of A is lost
- Durability: After a transaction has committed, the changes to the database persist even in case of system failure.
- Commit only after all changes are permanent:
  - either written to log file or directly to database
  - database must recover in case of a crash

Locks

- A lock is a mechanism to control concurrency on a data item.
- Two types of locks on a data item A:
  - exclusive – $xL(A)$: data item A can be both read and written
  - shared – $sL(A)$: data item A can only be read.
- Lock request are made to concurrency control manager.
- Transaction is blocked until lock is granted.
- Unlock A – $uL(A)$: release the lock on a data item A

Lock Compatibility

- Lock compatibility matrix:

$T_1 \downarrow \quad T_2 \rightarrow$	shared	exclusive
shared	true	false
exclusive	false	false

- T_1 holds shared lock on A:
  - shared lock is granted to T_2
  - exclusive lock is not granted to T_2
- T_2 holds exclusive lock on A:
  - shared lock is not granted to T_2
  - exclusive lock is not granted to T_2
- Shared locks can be shared by any number of transactions.

Locking Protocol

- Example transaction T_2 with locking:
  1. $sL(A)$, $R(A)$, $uL(A)$
  2. $sL(B)$, $R(B)$, $uL(B)$
  3. $print(A + B)$
- T_2 uses locking, but is not serializable
  - A and/or B could be updated between steps 1 and 2
  - printed sum may be wrong
- Locking protocol:
  - set of rules followed by all transactions while requesting/releasing locks
  - locking protocol restricts the set of possible schedules

Pitfalls of Locking Protocols – Deadlock

- Example: two concurrent money transfers
  - T_1: $R(A), A \leftarrow A + 10, R(B), B \leftarrow B - 10, W(A), W(B)$
  - T_2: $R(B), B \leftarrow B + 50, R(A), A \leftarrow A - 50, W(A), W(B)$
  - possible concurrent scenario with locks:
    $T_1.xL(A), T_1.R(A), T_2.xL(B), T_2.R(B), T_2.xL(A), T_1.xL(B), \ldots$
  - T_1 and T_2 block each other – no progress possible
- Deadlock: situation when transactions block each other
- Handling deadlocks:
  - one of the transactions must be rolled back (i.e., undone)
  - rolled back transaction releases locks

Pitfalls of Locking Protocols – Starvation

- Starvation: transaction continues to wait for lock
- Examples:
  - the same transaction is repeatedly rolled back due to deadlocks
  - a transaction continues to wait for an exclusive lock on an item while a sequence of other transactions are granted shared locks
- Well-designed concurrency manager avoids starvation.

Two-Phase Locking

- Protocol that guarantees serializability.
- Phase 1: growing phase
  - transaction may obtain locks
  - transaction may not release locks
- Phase 2: shrinking phase
  - transaction may release locks
  - transaction may not obtain locks

Two-Phase Locking – Example

- Example: two concurrent money transfers
  - T_1: $R(A), A \leftarrow A + 10, R(B), B \leftarrow B - 10, W(A), W(B)$
  - T_2: $R(A), A \leftarrow A - 50, R(B), B \leftarrow B + 50, W(A), W(B)$
- Possible two-phase locking schedule:
  1. $T_1 : xL(A), xL(B), R(A), R(B), W(A \leftarrow A + 10), uL(A)$
  2. $T_2 : xL(A), R(A), xL(B)$ *(wait)*
  3. $T_1 : W(B \leftarrow B - 10), uL(B)$
  4. $T_2 : R(B), W(A \leftarrow A - 50), W(B \leftarrow B + 50), uL(A), uL(B)$
- Equivalent serial schedule: T_1, T_2

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Concurrency Tuning Goals

- Performance goals:
  - reduce blocking (one transaction waits for another to release its locks)
  - avoid deadlocks and rollbacks
- Correctness goals:
  - serializability: each transaction appears to execute in isolation
  - note: correctness of serial execution must be ensured by the programmer!

Trade-off between performance and correctness!

Ideal Transaction

- Acquires few locks.
- Favors shared locks over exclusive locks.
  - only exclusive locks create conflicts
- Acquires locks with fine granularity.
  - granularities: table, page, row
  - reduces the scope of each conflict
- Holds locks for a short time.
  - reduce waiting time

Lock Tuning

1. Eliminate unnecessary locks
2. Control granularity of locking
3. Circumvent hot spots
4. Isolation guarantees and snapshot isolation
5. Split long transactions

1. Eliminate Unnecessary Locks

- Lock overhead:
  - memory: store lock control blocks
  - CPU: process lock requests
- Locks not necessary if
  - only one transaction runs at a time, e.g., while loading the database
  - all transactions are read-only, e.g., decision support queries on archival data

2. Control Granularity of Locking

- Locks can be defined at different granularities:
  - row-level locking (also: record-level locking)
  - page-level locking
  - table-level locking
- Fine-grained locking (row-level):
  - good for short online-transactions
  - each transaction accesses only a few records
- Coarse-grained locking (table-level):
  - avoid blocking long transactions
  - avoid deadlocks
  - reduced locking overhead

Lock Escalation

- Lock escalation: (SQL Server and DB2 UDB)
  - automatically upgrades row-level locks into table locks if number of row-level locks reaches predefined threshold
  - lock escalation can lead to deadlock
- Oracle does not implement lock escalation.

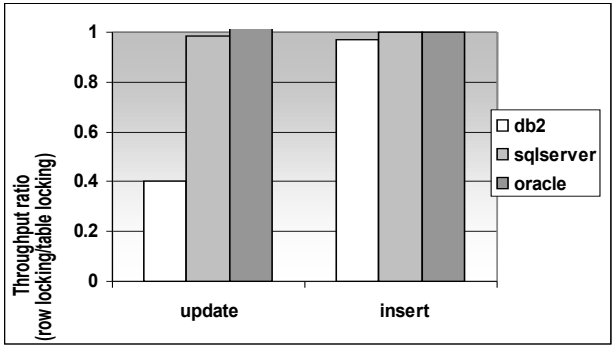
Granularity Tuning Parameters

1. Explicit control of the granularity:
   - within transaction: statement within transaction explicitly requests a table-level lock, shared or exclusive (Oracle, DB2)
   - across transactions: lock granularity is defined for each table; all transactions accessing this table use the same granularity (SQL Server)
2. Escalation point setting:
   - lock is escalated if number of row-level locks exceeds threshold (escalation point)
   - escalation point can be set by database administrator
   - rule of thumb: high enough to prevent escalation for short online transactions
3. Lock table size:
   - maximum overall number of locks can be limited
   - if the lock table is full, system will be forced to escalate

Overhead of Table vs. Row Locking

- Experimental setting:
  - `accounts(number,branchnum,balance)`
  - clustered index on account number
  - 100,000 rows
  - SQL Server 7, DB2 v7.1 and Oracle 8i on Windows 2000
  - lock escalation switched off
- Queries: (no concurrent transactions!)
  - 100,000 updates (1 query)
    example: `update accounts set balance=balance*1.05`
  - 100,000 inserts (100,000 queries)
    example: `insert into accounts values(713,15,2296.12)`

Overhead of Table vs. Row Locking

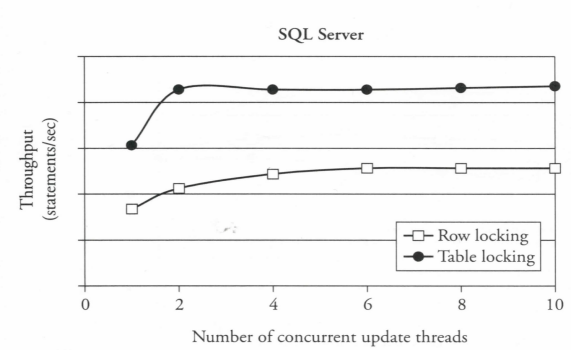


- Row locking (100k rows must be locked) should be more expensive than table locking (1 table must be locked).
- SQL Server, Oracle: recovery overhead (logging changes) hides difference in locking overhead
- DB2: low overhead due to logical logging of updates, difference in locking overhead visible

Experiment: Fine-Grained Locking

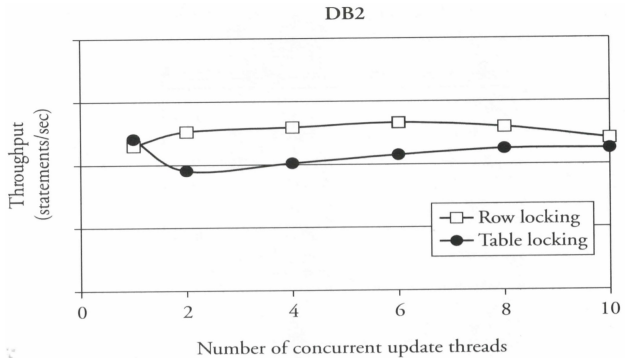
- Experimental setting:
  - table with bank accounts
  - clustered index on account number
  - long transaction (summation of account balances)
  - multiple short transactions (debit/credit transfers)
  - parameter: number of concurrent transactions
  - SQL Server 7, DB2 v7.1 and Oracle 8i on Windows 2000
  - lock escalation switched off

Experiment: Fine-Grained Locking



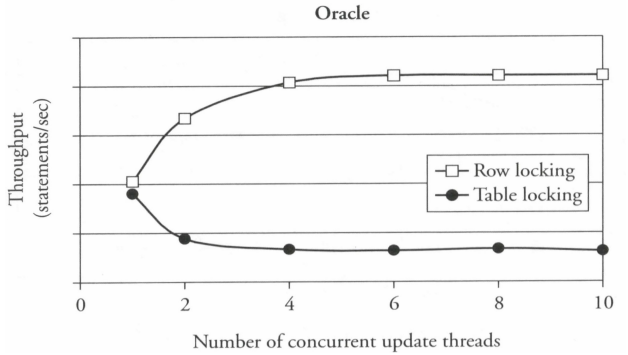
- Serializability with row locking forces key range locks.
- Key range locks are performed in clustered index.
- SQL Server: Clustered index is sparse, thus whole pages are locked.
- Row-level locking only slightly increases concurrency.
- Table-locking prevents rollback for summation query.

Experiment: Fine-Grained Locking



- Row locking slightly better than table locking.
- DB2 automatically selects locking granularity if not forced manually.
  - index scan in this experiment leads to row-level locking
  - table scan would lead to table-level locking

Experiment: Fine-Grained Locking



- Oracle uses snapshot isolation: summation query not in conflict with short transactions.
- Table locking: short transactions must wait.

3. Circumvent Hot Spots

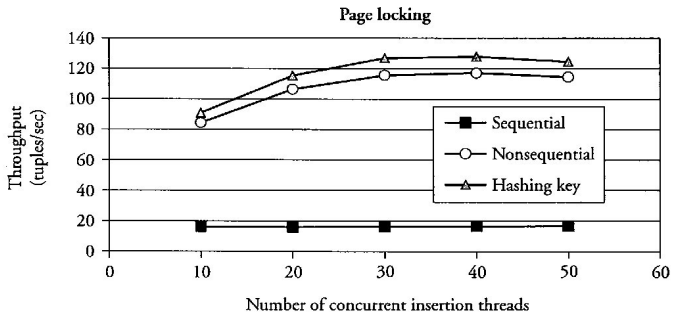
- Hot spot: items that are
  - accessed by many transactions
  - updated at least by some transactions
- Circumventing hot spots:
  - access hot spot as late as possible in transaction
    (reduces waiting time for other transactions since locks are kept to the end of a transaction[1])
  - use partitioning, e.g., multiple free lists
  - use special database facilities, e.g., latch on counter

[1] In 2-phase locking, the locks need only be held till the end of the growing phase; if the locks are held till the end of the transaction, the resulting schedule is *cascadeless* (in addition to *serializable*), which is desirable.

Partitioning Example: Distributed Insertions

- Insert contention: last table page is bottleneck
  - appending data to heap file (e.g., log files)
  - insert records with sequential keys into table with B^+-tree
- Solutions:
  - use clustered hash index
  - if only B^+ tree available: use hashed insertion time as key
  - use row locking instead of page locking
  - if reads are always table scans: define many insertion points
    (composite index on random integer $(1..k)$ and key attribute)

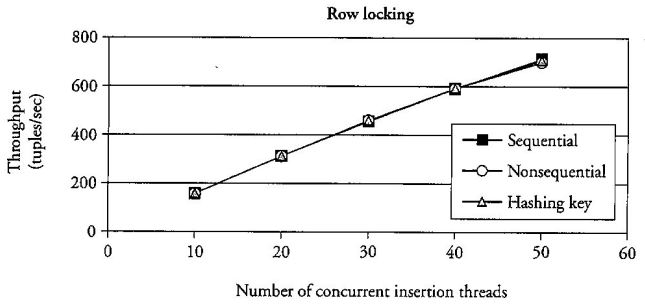
Experiment: Multiple Insertion Points and Page Locking



- Sequential: clustered B^+-tree index and key in insert order
- Non-sequential: clustered B^+-tree, key independent of insert order
- Hashing: composite index on random integer $(1..k)$ and key attribute
- Page locking and sequential keys: insert contention!

SQL Server 7 on Windows 2000

Experiment: Multiple Insertion Points and Row Locking



- No insert contention with row locking.

SQL Server 7 on Windows 2000

Partitioning Example: DDL Statements and Catalog

- Catalog: information about tables, e.g., names, column widths
- Data definition language (DDL) statements must access catalog
- Catalog can become hot spot
- Partition in time: avoid DDL statements during heavy system activity

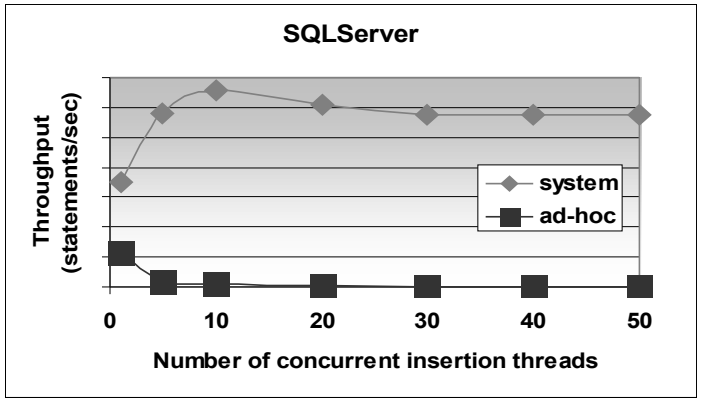
Partitioning Example: Free Lists

- Lock contention on free list:
  - free list: list of unused database buffer pages
  - a thread that needs a free page locks the free list
  - during the lock no other thread can get a free page
- Solution: Logical partitioning
  - create several free lists
  - each free list contains pointers to a portion of free pages
  - a thread that needs a free page randomly selects a list
  - with n free list the load per list is reduced by factor $1/n$

System Facilities: Latch on Counter

- Example: concurrent inserts with unique identifier
  - identifier is created by a counter
  - 2-phase locking: lock on counter is held until transaction ends
  - counter becomes hot spot
- Databases allow to hold a latch on the counter.
  - latch: exclusive lock that is held only during access
  - eliminates bottleneck but may introduce gaps in counter values
- Counter gaps with latches:
  - transaction T_1 increments counter to i
  - transaction T_2 increments counter to $i+1$
  - if T_1 aborts now, then no data item has identifier i

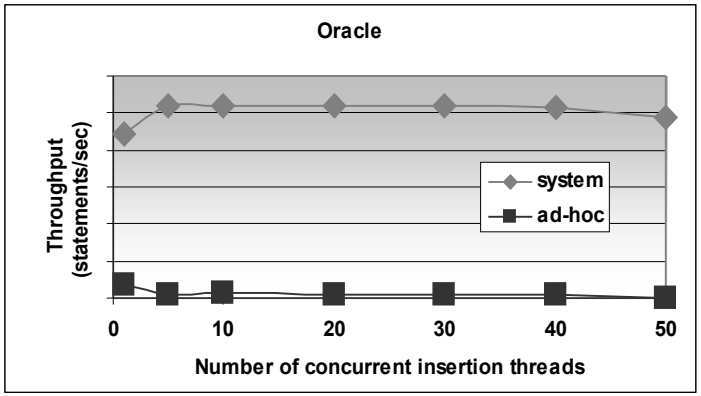
Experiment: Latch vs. Lock on Counter



- System (=latch): use system facility for generating counter values ("identity" in SQL Server)
- Ad hoc (=lock): increment a counter value in an ancillary table

SQL Server 7 on Windows 2000

Experiment: Latch vs. Lock on Counter



- System (=latch): use system facility for generating counter values ("sequence" in Oracle)
- Ad hoc (=lock): increment a counter value in an ancillary table

Oracle 8i EE on Windows 2000

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Undesirable Phenomena of Concurrent Transactions

- Dirty read
  - transaction reads data written by concurrent uncommitted transaction
  - problem: read may return a value that was never in the database because the writing transaction aborted
- Non-repeatable read
  - different reads on the same item within a single transaction give different results (caused by other transactions)
  - e.g., concurrent transactions T_1: $x = R(A)$, $y = R(A)$, $z = y - x$ and T_2: $W(A = 2 * A)$, then z can be either zero or the initial value of A (should be zero!)
- Phantom read
  - repeating the same query later in the transaction gives a different set of result tuples
  - other transactions can insert new tuples during a scan
  - e.g., "Q: get accounts with *balance* > 1000" gives two tuples the first time, then a new account with *balance* > 1000 is inserted by an other transaction; the second time Q gives three tuples

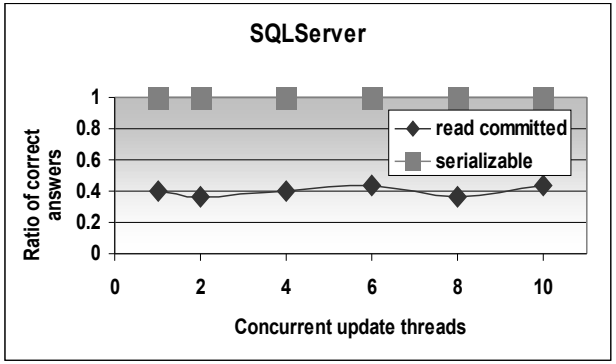
Isolation Guarantees (SQL Standard)

- Read uncommitted: dirty, non-repeatable, phantom
  - read locks released after read; write locks downgraded to read locks after write, downgraded locks released according to 2-phase locking
  - reads may access uncommitted data
  - writes do not overwrite uncommitted data
- Read committed: non-repeatable, phantom
  - read locks released after read, write locks according to 2-phase locking
  - reads can access only committed data
  - cursor stability: in addition, read is repeatable within single `SELECT`
- Repeatable read: phantom
  - 2-phase locking, but no range locks
  - phantom reads possible
- Serializable:
  - none of the undesired phenomenas can happen
  - enforced by 2-phase locking with range locks

Experiment: Read Commit vs. Serializable

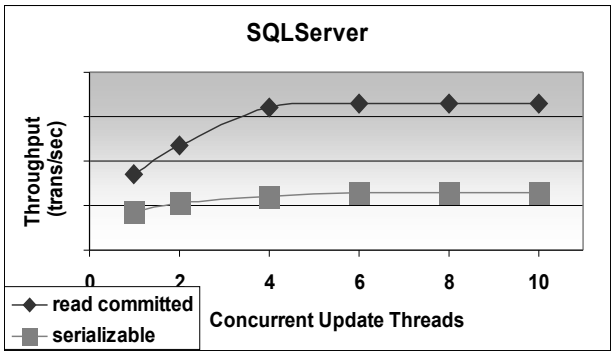
- Experimental setup:
  - T1: summation query: `SELECT SUM(balance) FROM Accounts`
  - T2: money transfers between accounts
  - row level locking
- Parameter: number of concurrent threads
- Measure:
  - percentage of correct answers (over multiple tries)
  - measure throughput

Experiment: Read Commit vs. Serializable



- Read committed allows sum of account balances after debit operation has taken place but before corresponding credit operation is performed – incorrect sum!

Experiment: Read Commit vs. Serializable



- Read committed: faster, but incorrect answers
- Serializable: always correct, but lower throughput

When To Weaken Isolation Guarantees?

- Query does not need exact answer (e.g., statistical queries)
  - example: count all accounts with balance$>$ \$1000.
  - read committed is enough!
- Transactions with human interaction
  - example: flight reservation system
  - price for serializability too high!

Example: Flight Reservation System

- Reservation involves three steps:
  1. retrieve list of available seats
  2. let customer decide
  3. secure seat
- Single transaction:
  - seats are locked while customer decides
  - all other customers are blocked!
- Two transactions: (1) retrieve list, (2) secure seat
  - seat might already be taken when customer wants to secure it
  - more tolerable than blocking all other customers

Snapshot Isolation for Long Reads – The Problem

- Consider the following scenario in a bank:
  - read-only query Q: `SELECT SUM(deposit) FROM Accounts`
  - update transaction T: money transfer between customers A and B
- 2-Phase locking inefficient for long read-only queries:
  - read-only queries hold lock on all read items
  - in our example, T must wait for Q to finish (Q blocks T)
  - deadlocks might occur:
    $T.xL(A)$, $Q.sL(B)$, $Q.sL(A)$ - wait, $T.xL(B)$ - wait
- Read-committed may lead to incorrect results:
  - Before transactions: $A = 50, B = 30$
  - $Q : sL(A), R(A) = 50, uL(A)$
  - $T : xL(A), xL(B), W(A \leftarrow A + 20), W(B \leftarrow B - 20), uL(A), uL(B)$
  - $Q : sL(B), R(B) = 10, uL(B)$
  - sum computed by Q for $A + B$ is 60 (instead of 80)

Snapshot Isolation for Long Reads

- Snapshot isolation: correct read-only queries without locking
  - read-only query Q with snapshot isolation
  - remember old values of all data items that change after Q starts
  - Q sees the values of the data items when Q started
- Example: bank scenario with snapshot isolation
  - Before transactions: $A = 50, B = 30$
  - $Q : R(A) = 50$
  - $T : xL(A), xL(B), W(A \leftarrow A + 20), W(B \leftarrow B - 20), uL(A), uL(B)$
  - $Q : R(B) = 30$ (read old value)
  - sum computed by Q for $A + B$ is 80 as it should be

Concurrency in Oracle

- "Read committed" in Oracle means:
  - non-repeatable and phantom reads are possible at the transaction level, but not within a single SQL statement
  - update conflict: if row is already updated, wait for updating transaction to commit, then update new row version (or ignore row if deleted) – no rollback!
  - possibly inconsistent state: transaction sees updates of other transaction only on the rows that itself updates
- "Serializable" in Oracle means:
  - phenomena: none of the three undesired phenomena can happen
  - update conflict: if two transactions update the same item, the transaction that updates it later must abort – rollback!
  - not serializable: snapshot isolation does not guarantee full serializability (skew writes)
- Similar in PostgreSQL.

Skew Writes: Snapshot Isolation Not Serializable

- Example: $A = 3, B = 17$
  - $T1 : A \leftarrow B$
  - $T2 : B \leftarrow A$
- Serial execution:
  - order $T1, T2$: $A = B = 17$
  - order $T2, T1$: $A = B = 3$
- Snapshot isolation:
  - $T1 : R(B) = 17$
  - $T2 : R(A) = 3$
  - $T1 : W(A \leftarrow 17)$
  - $T2 : W(B \leftarrow 3)$
  - result: $A = 17, B = 3$ (different from serial execution)

Snapshot Isolation

- Advantages: (assuming "serializable" of Oracle)
  - readers do not block writers (as with locking)
  - writers do not block readers (as with locking)
  - writers block writers only if they update the same row
  - performance similar to read committed
  - no dirty, non-repeatable, or phantom reads
- Disadvantages:
  - system must write and hold old versions of modified data (only date modified between start and end of read-only transaction)
  - does not guarantee serializability for read/write transactions
- Implementation example: Oracle 9i
  - no overhead: leverages before-image in rollback segment
  - expiration time of before-images configurable, "snapshot too old" failure if this value is too small

Serializable Snapshot Isolation – Workaround and Solution

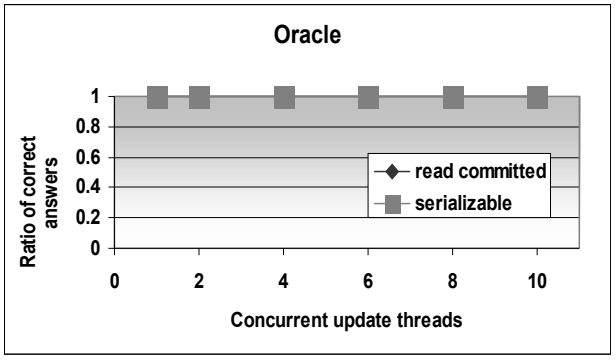
- Workarounds to get true serializability with snapshot isolation:
  - create additional data item that is updated by conflicting transactions (e.g., maintain sum of A and B in our skew write example)
  - use exclusive locks for dangerous reads (e.g., use exclusive lock for reading A and B in our skew write example)
- Problem: requires static analysis of all involved transactions
- Solution: serializable snapshot isolation[2]
  - conflicts are detected by the system
  - conflicting transactions are aborted
  - leads to more aborts, but keeps other advantages of snapshot isolation
- PostgreSQL (starting with version 9.1)
  - REPEATABLE READ is snapshot isolation
  - SERIALIZABLE is serializable snapshot isolation

[2] Michael J. Cahill, Uwe Rhm, Alan David Fekete: Serializable isolation for snapshot databases. SIGMOD Conference 2008: 729-738

Snapshot Isolation – Summary

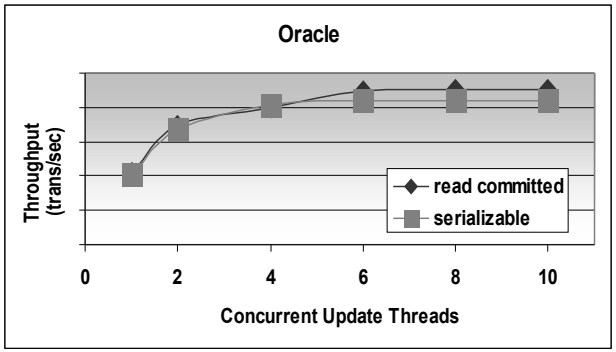
- Considerable performance advantages since reads are never blocked and do not block other transactions.
- Not fully serializable, although no dirty, non-repeatable, or phantom reads.
- Serializable snapshot isolation: fully serializable at the cost of more aborted transactions.

Experiment: Read Commit vs. Serializable



- Summation query with concurrent transfers between bank accounts.
- Oracle snapshot isolation: read-only summation query is not disturbed by concurrent transfer queries
- Summation (read-only) queries always give exact answer.

Experiment: Read Commit vs. Serializable



- Both "read commit" and "serializable" use snapshot isolation.
- "Serializable" rolls back transactions in case of write conflict.
- Summation queries always give exact answer.

Outline

1 Concurrency Tuning
- Introduction to Transactions
- Lock Tuning
- Weaken Isolation Guarantees
- Transaction Chopping

Chopping Long Transactions

- Shorter transactions
  - request less locks (thus they are less likely to be blocked or block an other transaction)
  - require other transactions to wait less for a lock
  - are better for logging
- Transaction chopping:
  - split long transactions into short ones
  - don't scarify correctness

Terminology

- Transaction: sequence of disc accesses (read/write)
- Piece of transaction: consecutive subsequence of database access.
  - example transaction $T : R(A), R(B), W(A)$
  - $R(A)$ and $R(A), R(B)$ are pieces of T
  - $R(A), W(A)$ is not a piece of T (not consecutive)
- Chopping: partitioning transaction it into pieces.
  - example transaction $T : R(A), R(B), W(A)$
  - $T_1 : R(A), R(B)$ and $T_2 : W(A)$ is a chopping of T

Split Long Transactions – Example 1

- Bank with accounts and branches:
  - each account is assigned to exactly one branch
  - branch balance is sum of accounts in that branch
  - customers can take out cash during day
- Transactions over night:
  - update transaction: reflect daily withdrawals in database
  - balance checks: customers ask for account balance (read-only)
- Update transaction T_{blob}
  - updates all account balances to reflect daily withdrawals
  - updates the respective branch balances
- Problem: balance checks are blocked by T_{blob} and take too long

Split Long Transactions – Example 1

- Solution: split update transactions T_{blob} into many small transactions
- Variant 1: each account update is one transaction which
  - updates one account
  - updates the respective branch balance
- Variant 2: each account update consists of two transactions
  - T_1 : update account
  - T_2 : update branch balance
- Note: isolation does not imply consistency
  - both variants maintain serializability (isolation)
  - variant 2: consistency (sum of accounts equal branch balance) compromised if only one of T_1 or T_2 commits.

Split Long Transactions – Example 2

- Bank scenario as in Example 1.
- Transactions:
  - update transaction: each transaction updates one account and the respective branch balance (variant 1 in Example 1)
  - balance checks: customers ask for account balance (read-only)
  - consistency (T'): compute account sum for each branch and compare to branch balance
- Splitting: T' can be split into transactions for each individual branch
- Serializability maintained:
  - consistency checks on different branches share no data item
  - updates leave database in consistent state for T'
- Note: update transaction can not be further split (variant 2)!
- Lessons learned:
  - sometimes transactions can be split without sacrificing serializability
  - adding new transaction to setting may invalidate all previous chopping

Formal Chopping Approach

- Assumptions: when can the chopping be applied?
- Execution rules: how must chopped transactions be executed?
- Chopping graph: which chopping is correct?

Assumptions for Transaction Chopping

1. Transactions: All transactions that run in an interval are known.
2. Rollbacks: It is known where in the transaction rollbacks are called.
3. Failure: In case of failure it is possible to determine which transactions completed and which did not.
4. Variables: The transaction code that modifies a program variable x must be reentrant, i.e., if the transaction aborts due to a concurrency conflict and then executes properly, x is left in a consistent state.

Execution Rules

1. Execution order: The execution of pieces obeys the order given by the transaction.
2. Lock conflict: If a piece is aborted due to a lock conflict, then it will be resubmitted until it commits.
3. Rollback: If a piece is aborted due to a rollback, then no other piece for that transaction will be executed.

The Transaction Chopping Problem

- Given: Set $A = \{T_1, T_2, \ldots, T_n\}$ of (possibly) concurrent transactions.
- Goal: Find a chopping B of the transactions in A such that any serializable execution of the transactions in B (following the execution rules) is equivalent so some serial execution of the transaction in A. Such a chopping is said to be correct.
- Note: The "serializable" execution of B may be concurrent, following a protocol for serializability.

Chopping Graph

- We represent a specific chopping of transactions as a graph.
- Chopping graph: undirected graph with two types of edges.
  - nodes: each piece in the chopping is a node
  - C-edges: edge between any two conflicting pieces
  - S-edges: edge between any two sibling pieces
- Conflicting pieces: two pieces p and p' conflict iff
  - p and p' are pieces of different original transactions
  - both p and p' access a data item x and at least one modifies it
- Sibling pieces: two pieces p and p' are siblings iff
  - p and p' are neighboring pieces of the same original transactions

Chopping Graph – Example

- Notation: chopping of possibly concurrent transactions.
  - original transactions are denoted as $T_1, T_2, \ldots$
  - chopping T_i results in pieces $T_{i1}, T_{i2}, \ldots$
- Example transactions: $(T_1 : R(x), R(y), W(y)$ is split into $T_{11}, T_{12})$
  - $T_{11} : R(x)$
  - $T_{12} : R(y), W(y)$
  - $T_2 : R(x), W(x)$
  - $T_3 : R(y), W(y)$
- Conflict edge between nodes
  - T_{11} and T_2 (conflict on x)
  - T_{12} and T_3 (conflict on y)
- Sibling edge between nodes
  - T_{11} and T_{22} (same original transaction T_1)

Rollback Safe

- Motivation: Transaction T is chopped into T_1 and T_2.
  - T_1 executes and commits
  - T_2 contains a rollback statement and rolls back
  - T_1 is already committed and will not roll back
  - in original transaction T rollback would also undo effect of piece T_1!
- A chopping of transaction T is rollback save if
  - T has no rollback statements or
  - all rollback statements are in the first piece of the chopping

Correct Chopping

Theorem (Correct Chopping)

A chopping is correct if it is rollback save and its chopping graph contains no SC-cycles.

- Chopping of previous example is correct (no SC-cycles, no rollbacks)
- If a chopping is not correct, then any further chopping of any of the transactions will not render it correct.
- If two pieces of transaction T are in an SC-cycle as a result of chopping T, then they will be in a cycle even if no other transactions (different from T) are chopped.

Private Chopping

- Private chopping: Given transactions $T_1, T_2, \ldots, T_n$. $T_{i1}, T_{i2}, \ldots, T_{ik}$ is a private chopping of T_i if
  - there is no SC-cycle in the graph with the nodes $\{T_1, \ldots, T_{i1}, \ldots, T_{ik}, \ldots, T_n\}$
  - T_i is rollback save
- Private chopping rule: The chopping that consists of $private(T_1), private(T_2), \ldots, private(T_n)$ is correct.
- Implication:
  - each transaction T_i can be chopped in isolation, resulting in $private(T_i)$
  - overall chopping is union of private choppings

Chopping Algorithm

1. Draw an S-edge between the R/W operations of a single transaction.
2. For each data item x produce a write list, i.e., a list of transactions that write this data item.
3. For each $R(x)$ or $W(x)$ in all transactions:
   (a) look up the conflicting transactions in the write list of x
   (b) draw a C-edge to the respective conflicting operations
4. Remove all S-edges that are involved in an SC-cycle.

Chopping Algorithm – Example

- Transactions: $(Rx = R(x), Wx = W(x))$
  - $T_1 : Rx, Wx, Ry, Wy$
  - $T_2 : Rx, Wx$
  - $T_3 : Ry, Rz, Wy$
- Write lists: $x{:}T_1, T_2;\ y{:}T_1, T_3;\ z{:}\emptyset$
- C-edges:
  - T_1: $Rx - T_2.Wx$, $Wx - T_2.Wx$, $Ry - T_3.Wy$, $Wy - T_3.Wy$
  - T_2: $Rx - T_1.Wx$ ($Wx - T_1.Wx$: see T_1)
  - T_3: $Ry - T_1.Wy$ ($Wy - T_1.Wy$: see T_1)
- Remove S-edges: T_1: $Rx - Wx$, $Ry - Wy$; T_2: $Rx - Wx$; T_3: $Ry - Rz, Rz - Wy$
- Final chopping:
  - $T_{11} : Rx, Wx;\ T_{12} : Ry, Wy$
  - $T_2 : Rx, Wx$
  - $T_3 : Ry, Rz, Wy$

Reordering Transactions

- Commutative operations:
  - changing the order does not change the semantics of the program
  - example: $R(y), R(z), W(y \leftarrow y + z)$ and $R(z), R(y), W(y \leftarrow y + z)$ do the same thing
- Transaction chopping:
  - changing the order of commutative operations may lead to better chopping
  - responsibility of the programmer to verify that operations are commutative!
- Example: consider $T_3 : Ry, Rz, Wy$ of the previous example
  - assume T_3 computes $y + z$ and stores the sum in y
  - then Ry and Rz are commutative and can be swapped
  - $T_3' : Rz, Ry, Wy$ can be chopped: $T_{31}' : Rz,\ T_{32}' : Ry, Wy$