Part III

Distributed DBS - Transaction Processing

6 Distributed DBS - Transaction Processing

Overview

Contents

6.1 Foundations

Foundations of TXN Management

A *Transaction* is a sequence of operations which represent a semantic unit and transfer a database from one consistent state to another consistent state adhering to the *ACID-principle*.

Aspects:

- Semantic integrity: consistent state must be reached after transaction, no matter if it succeeded or failed
- Process integrity: avoid failures due to concurrent parallel access by multiple users/transactions

Transactions: ACID Properties

- **A**tomicity means that a transaction can not be interrupted or performed only partially
  - TXN is performed in its entirety or not at all
- **C**onsistency to preserve data integrity
  - A TXN starts from a consistent database state and ends with a consistent database state
- **I**solation
  - Result of a TXN must be independent of other possibly running parallel TXNs
- **D**urability or persistence
  - After a TXN finished successfully (from the user's view) its results must be in the database and the effect can not be reversed

Commands of a TXN Language

- Begin of Transaction **`BOT`** (in SQL implicated by first statement)
- **`commit`**: TXN ends successfully
- **`abort`**: TXN must be aborted during processing

Problems with Processing Integrity

- Parallel accesses in multi-user DBMS can lead to the following problems
  - Non-repeatable reads
  - Dirty reads
  - The phantom problem
  - Lost updates

Non-repeatable Read

Example:

- Assertion: $X = A + B + C$ at the end of txn T_1
- X and Y are local variables
- T_i is txn i
- Integrity constraint on persistent data $A + B + C = 0$

Non-repeatable Read /2

T_1	T_2
$X := A$;	
	$Y := A/2$;
	$A := Y$;
	$C := C + Y$;
	`commit`;
$X := X + B$;	
$X := X + C$;	
`commit`;	

Dirty Read

T_1	T_2
`read`(X);	
$X := X + 100$;	
`write`(X);	
	`read`(X);
	$Y := Y + X$;
	`write`(Y);
	`commit`;
`abort`;	

The Phantom Problem

T_1	T_2
select count (*)	
into X	
from Employee;	
	insert
	into Employee
	values $(Meier, 50000, \cdots)$;
	commit;
update Employee	
set Salary $=$	
Salary $+10000/X$;	
commit;	

Lost Update

T_1	T_2	X
read(X);		10
	read(X);	10
$X := X + 1$;		10
	$X := X + 1$;	10
write(X);		11
	write(X);	11

Simplified TXN Model

Representation of (abstract) data object (values, tuples, pages) access

- **`read`**(A,x): assign value of DB object A to variable x
- **`write`**(x, A): assign value of x to DB object A

Example of a txn T:

> **`read`**(A, x); $x := x - 200$; **`write`**(x, A); **`read`**(B, y); $y := y + 100$; **`write`**(y, B);**`commit`**

Schedules: possible processing of two txns T_1, T_2:

- Serial schedule: T_1 before T_2 or T_2 before T_1
- Intertwined schedule: mixed execution of operations from both txns

Serializability

An intertwined schedule of a number of transactions is called **serializable**, if the effect of the intertwined schedule is identical to the effect of any of the possible serial schedules. The intertwined schedule is then called correct and **equivalent** to the serial schedule.

- Practical approaches for deciding about serializabilty most often only considering read/write operations and their conflicts $\rightarrow$ **Conflict Serializability**
- Considering other operations requires analysis of operations semantics
- Rules out subset of serializable schedules which are hard to detect

Conflicting Operations

T_1	T_2
`read` A	
	`read` A

independent of order

T_1	T_2
`read` A	
	`write` A

dependent on order

T_1	T_2
	`write` A
`read` A	

dependent on order

T_1	T_2
	`write` A
`write` A	

dependent on order

Conflict Serializability

A schedule s is called conflict-serializable, if the order of all pairs of conflicting operations is equivalent to the order of any serial schedule s' for the same transactions.

Tested using conflict graph $G(s) = (V, E)$ of schedule s:

1. Vertex set V contains all txns of s
2. Edge set E contains an edge for each pair of conflicting operations

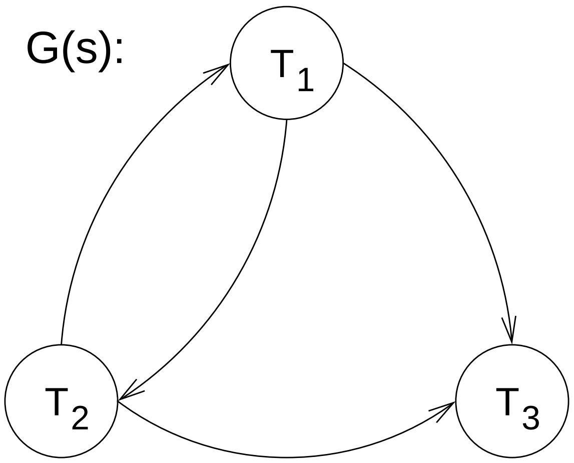
In serial schedules s' there can no cycles, i.e. if a cycle exists the schedule s can not be equivalent to a serial schedule and must be rejected.

Conflict Serializability: Example /1

T_1	T_2	T_3
r(y)		
		r(u)
	r(y)	
w(y)		
w(x)		
	w(x)	
	w(z)	
		w(x)

$$s = r_1(y)r_3(u)r_2(y)w_1(y)w_1(x)w_2(x)w_2(z)w_3(x)$$

Conflict Serializability: Example /2



Transaction Synchronization

1. Most common practical solution: Locking Protocols
   - TXNs get temporarily exclusive access to DB object (tuple, page, etc.)
   - DBMS manages temporary locks
   - Locking protocol grants cnflict serializabilty without further tests
2. In distributed DBMS also: timestamp-based protocols

Locking Protocols

Read and write locks using the following notation:

- $rl(x)$: read lock on object x
- $wl(x)$: write lock on object x

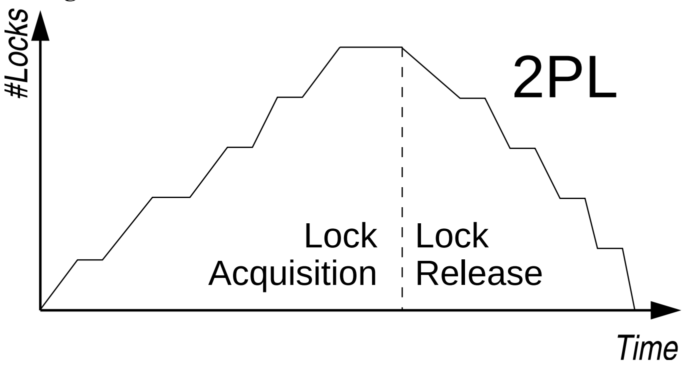
Unlock $ru(x)$ and $wu(x)$, often combined $u(x)$ *unlock* object x

Locks: Compatibility Matrix

- For basic locks

	$rl_i(x)$	$wl_i(x)$
$rl_j(x)$	$\surd$	—
$wl_j(x)$	—	—

2-Phase-Locking Protocol

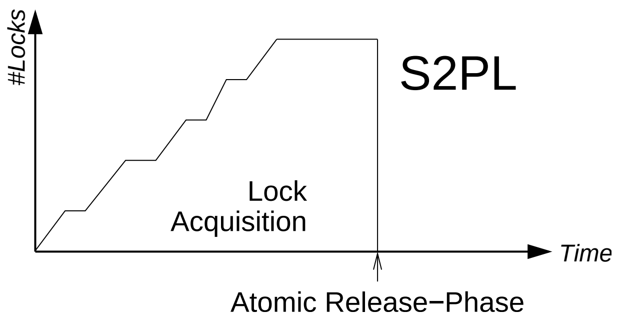


2-Phase-Locking: Example

T_1	T_2
$u(x)$	
	$wl(x)$
	$wl(y)$
	$\vdots$
	$u(x)$
	$u(y)$
$wl(y)$	
$\vdots$	

Strict 2-Phase-Locking

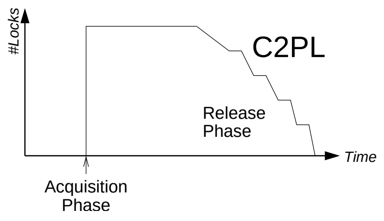
Current practice in most DBMS:

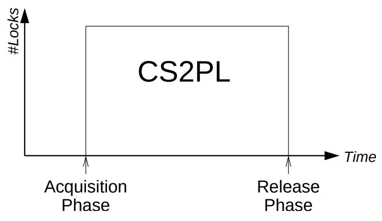


Avoids cascading aborts!

Conservative 2-Phase-Locking

To avoid Deadlocks:





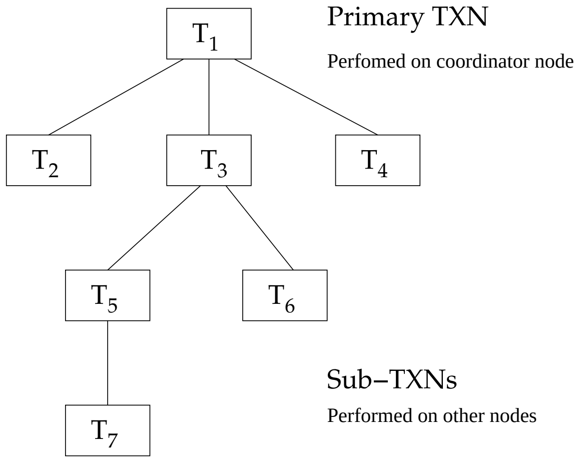
Most often not practical!

6.2 Distributed TXN Processing

Distributed TXN Processing

- In DDBS one TXN can run on multiple nodes
- Distributed synchronization required for parallel TXNs required
- Commit as atomic event → same result on all nodes
- Deadlocks (blocking/blocked TXNs) harder to detect

Structure of Distributed TXNs



Distributed Synchronization with Locking

- One central node for lock management
  - Dedicated node becomes bottleneck
  - Low node autonomy
  - High number of messages for lock acquisition/release
- Distributed lock management on all nodes
  - Possible, if data (relations, fragments) is stored non-redundantly
  - Special strategies for replicated data
  - Disadvantage: deadlocks are hard to detect
- Latter, i.e. distributed S2PL, is state-of-the-art
- Alternative: Timestamp-based Synchronisation

Timestamp-based Synchronization

- Unique timestamps are sequentially assigned to TXNs
- For each data object (tuple, page, etc.) x two values are stored:
  - **`max-r-scheduled`**$[x]$: timestamp of last TXN performing a read operation on x
  - **`max-w-scheduled`**$[x]$: timestamp of last TXN performing a write operation on x

Timestamp-Ordering

An operation $p_i[x]$ can be performed before a conflicting operation $q_k[x]$ iff $ts(T_i) < ts(T_k)$. Otherwise, $q_k[x]$ must be rejected.

T_1	T_2	T_3	A		B		C	
			`mrs`	**`mws`**	**`mrs`**	**`mws`**	**`mrs`**	**`mws`**
$ts = 200$	$ts = 150$	$ts = 175$	0	0	0	0	0	0
`read` B			0	0	200	0	0	0
	`read` A		150	0	200	0	0	0
		`read` C	150	0	200	0	175	0
`write` B			150	0	200	200	175	0
`write` A			150	200	200	200	175	0
	`write` $C \Downarrow$		150	200	200	200	175	$\Downarrow$
	`abort`		150	200	200	200	175	0

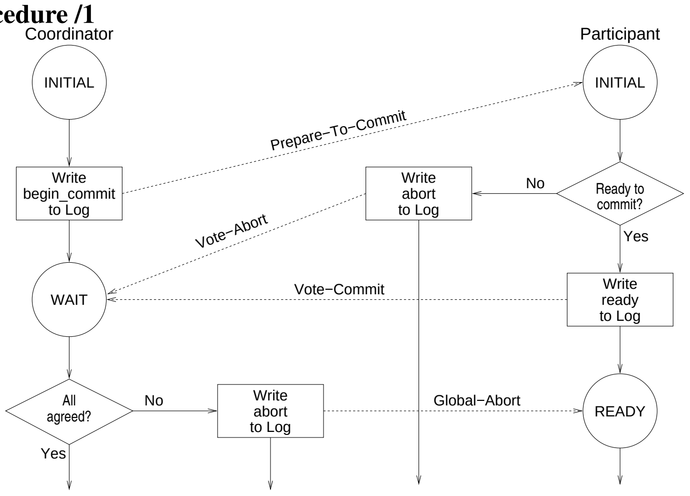
Distributed Commit

- Synchronization provides **C**onsistency and **I**solation
- Commit Protocol provides **A**tomicity and **D**urability
- Requirements in DDBS:
  - All participating nodes of one TXN with same result (**`Commit`**, **`Abort`**)
  - **`Commit`** only if all nodes vote "‘yes"’
  - **`Abort`** if at least one node votes "‘no"’
- X/open XA standard for 2-Phase-Commit Protocol (used in DBMS, request brokers, application servers, etc.)

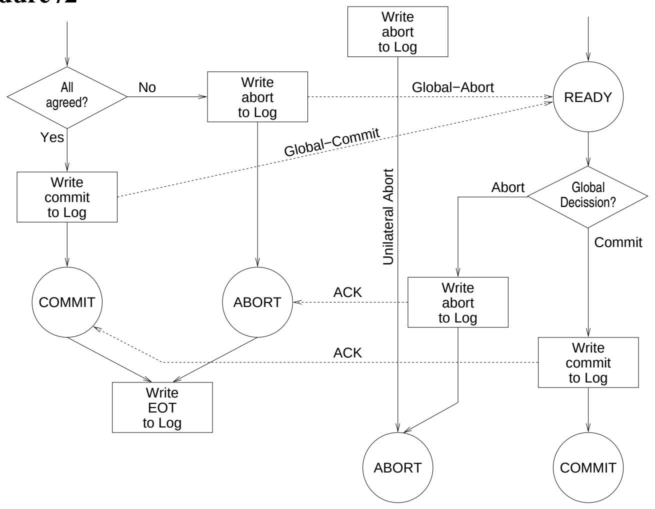
2-Phase-Commit Protocol (2PC)

- Roles: 1 coordinator, several other participants
- Procedure:
  1. *Commit Request Phase*
     (a) Coordinator queries all participants, if **`Commit`** can be executed
     (b) Participants send their local reply message, if they agree with the commit
  2. *Commit Phase*
     (a) Coordinator decides globally: (all messages **`Commit`** $\rightarrow$ **`Global-Commit`**; at least one **`Abort`** $\rightarrow$ **`Global-Abort`**
     (b) Participants which voted "‘yes"’ have to wait for final result

2PC: Procedure /1



2PC: Procedure /2

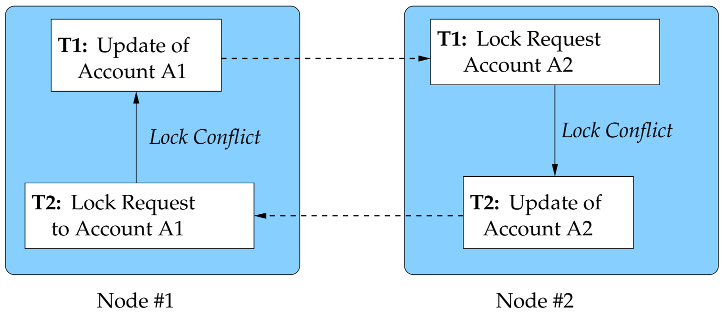


3-Phase-Commit Protocol (3PC)

- Possible problem with 2PC: if coordinator fails while other participants are in **`READY`** state, these may **block indefinitely**
- Solution:
  - Intermediate **`PRE-COMMIT`** phase added, so that a certain number K (system parameter) of other participants know about possible positive result
  - Timeout values to avoid blocking: if communication timed out an no other node is in **`PRE-COMMIT`** state, TXN must abort
- Disadvantagees
  - 3PC has increased message number
  - Still problematic in case of network partitioning

6.3 Transaction Deadlocks

Transaction Deadlocks



T1: Update of Account A1
T1: Lock Request Account A2
Lock Conflict
Lock Conflict
T2: Lock Request to Account A1
T2: Update of Account A2
Node #1
Node #2

Dealing with TXN Deadlocks

- **Deadlock Prevention:**
  - Implement TXN management in a way that makes deadlocks impossible, e.g. lock pre-claiming in Conservative 2PL
  - Most often not practical or efficient
- **Deadlock Avoidance:**
  - TXN management reacts to possible deadlock situations, e.g. timeout for lock requests
  - Easy to implement, but overly restrictive and not always efficient
- **Deadlock Detection and Resolution:**
  - TXM management detects deadlocks, e.g. using TXN Wait graphs
  - Efficient, but harder to implement - especially for DDBMS

Deadlock Avoidance: Timeouts

- Reset TXN if waiting time for lock acquisition exceeds pre-defined threshold
- Problem: setting the timeout threshold
  - Too short: unnecessary aborts
  - Too long: system throughput declines
- Timeout threshold specific for certain applications (typical TXN running times must be considered)
- Implemented in most commercial systems

Deadlock Avoidance: Timestamp-based

- Alternative: consider unique TXN timestamps assigned to each TXN with `BOT`
- Avoid deadlocks in case of lock conflict considering timestamp:
- In case of conflict only the
  - younger TXN (Wound/Wait)
  - older TXN (Wait/Die)

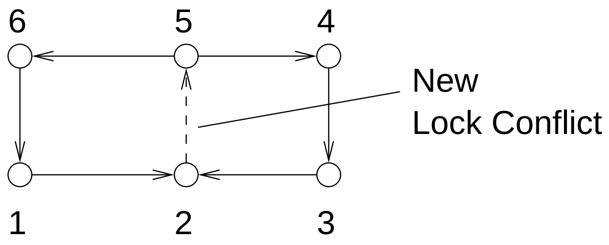
  will continue
- Can be combined with timeout (before timestamp check)

Deadlock Detection

- Common approach
  - Protocol each lock conflict in wait graph (nodes are TXNs, directed edge $T_1 \rightarrow T_2$ means that T_1 waits for a lock held by T_2
  - Deadlocks exist iff there is a cycle in the wait graph
  - Lock request leads to lock conflict $\rightarrow$ insert new edge in wait graph $\rightarrow$ check for cycles containing new edge

Deadlock Resolution

- Wait graph:



- Resolution choosing one TXN to abort upon following criteria
  - Number of resolved cycles
  - Age of TXN
  - Effort to rollback TXN
  - Priority of TXN, ...

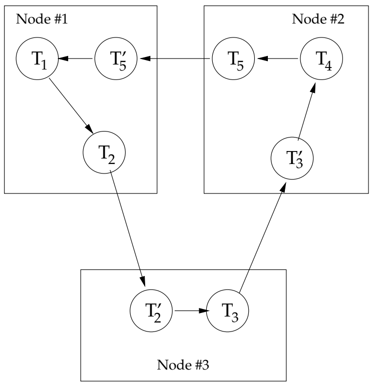
Centralized Deadlock Detection

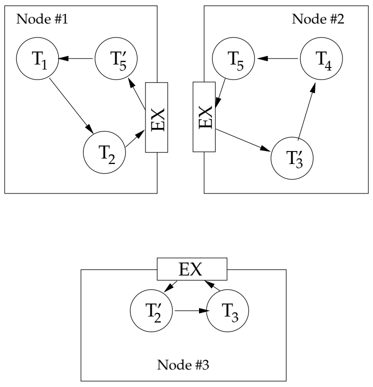
- Wait graph stored on one dedicated node
- Decrease number of messages by sending frequent bundles of collected lock waits
- Problems:
  - Late detection of deadlocks
  - Phantom-Deadlocks
  - Limited availability and node autonomy

Distributed Deadlock Detection

- Avoids dependency on global node
- Hard to realize: cycles can exist across different nodes $\rightarrow$ wait graph information needs to be exchanged between nodes
- Obermarck-Verfahren (System R*)
  - Each node with its own *deadlock detector*
  - Detector manages local wait graph + dependencies on locks of external transactions: one special node **`EX`** represents external transactions
  - Local deadlocks (not involving **`EX`** node) can be detected locally
  - Cycle including **`EX`** node may hint at distributed deadlock: cycle sub-graph is sent to node which created local cycle and possibly further to other involved nodes, until **`EX`** is resolved and decision can be made

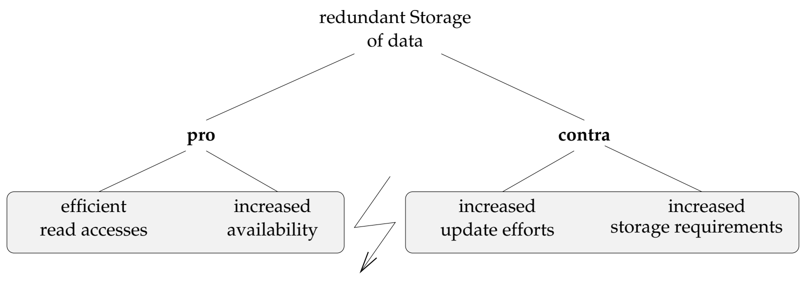
Distributed Wait Graphs





6.4 Transactional Replication

Motivation for Replication



- Replication transparency $\rightsquigarrow$ DDBMS manages updates on redundant data

Transactional Replication

- Data integrity must be granted across replicas $\rightsquigarrow$ 1-Copy-Equivalence and 1-Copy-Serializability
- Problems to be solved:
  - How to efficiently update the copies?
  - How to handle failures (single nodes, network fragmentation)?
  - How to synchronize concurrent updates?
- Approaches
  - ROWA
  - Primary Copy
  - Consensus approaches
  - Others: Snapshot-, Epidemic, and Lazy Replication

ROWA Synchronization

- "‘Read One Write All"’
  - **one** logial read operation $\rightarrow$ one physical read operation on **any** copy ("‘read one"’), where read access can be performed most efficiently (local or closest copy)
  - **one** logical write operation $\rightarrow$ physical write operations on **all** copies ("‘write all"’)
  - Equivalent to "‘normal"’ transaction synchronization: all updates within **one** transaction context

ROWA: Evaluation

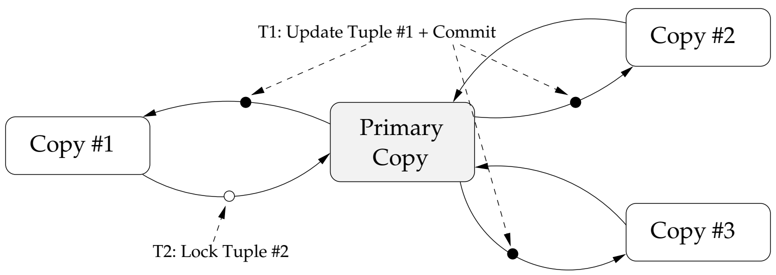
- Advantages
  - Approach is part of normal TXN processing
  - Easy to implement
  - Grants full consistency (1-Copy-Serializability)
  - Efficient local read operations
- Disadvantages
  - Updates dependent on availabilty of **all** nodes storing replicated data
  - Longer run-time of update TXNs $\rightsquigarrow$ decreased throughput and availabilty
  - Deadlocks more likely

Primary-Copy Replication

- Also: Master-Slave Replication
- First implemented in Distributed INGRES (Stonebraker 1979)
- Basic principle
  - Designation of a primary (master) copy ("‘original version"’); all secondary (slave) copies are derived from that original
  - All updates must first be performed on primary copy (lock relevant data objects, perform update, release locks)
  - In case of successful update, primary copy forwards updates **asychronously** to all secondary copies in separate TXNs
  - Read operations are performed locally

Primary-Copy: Example

- Secondary copies get changes from update queue (FIFO) $\rightsquigarrow$ consistency with primary copy
- In case of failure of secondary node, queue is processed when node is restarted



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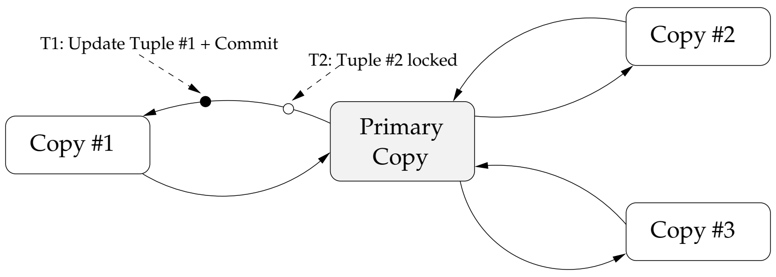

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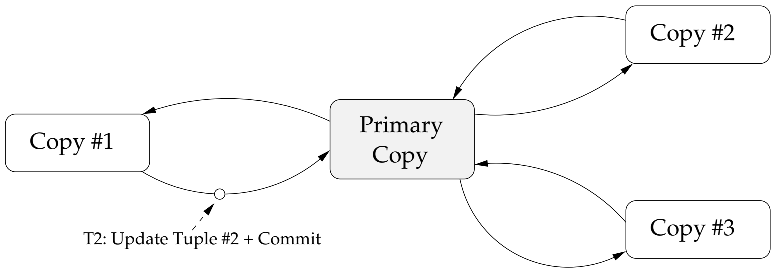

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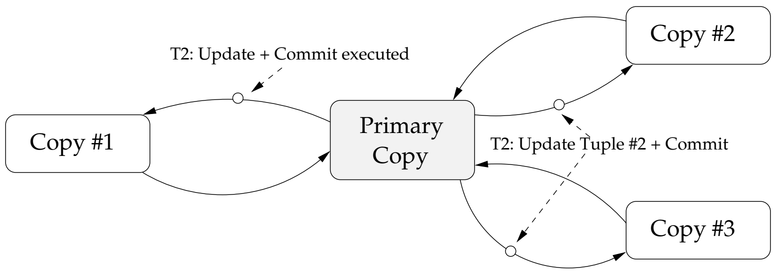

Primary-Copy: Evaluation

- Advantages compared to ROWA
  - No dependence on availability of all secondary nodes
  - Better throughput, less conflicts
  - Failure of primary copy $\leadsto$ one of the secondary copies can become primary copy
- Disadvantages
  - Read consistency not granted
    - Often acceptable, because state of secondary copies is consistent regarding previous point in time ("‘snapshot semantics"’)
    - Read-consistency can be implemented by requesting read locks from primary copy $\leadsto$ decreases advantage of local reads
  - Network fragmentation: cut-off subnet without primary copy can not continue, though it may have greater number of nodes

Consensus Approaches

- To avoid problems in case of network fragmentation and dependence on one centralized node
- Basic idea: update can be processed, if a node gets necessary if majority of nodes with copies agree
- Based on voting - overall number of possible votes: quorum Q
  - Required number of votes for read operations: read quorum Q_R
  - Required number of votes for update operations: update quorum Q_U
- Quorum-Overlap-Rules: grants 1-Copy-Serializablity
  1. $Q_R + Q_U > Q$
  2. $Q_U + Q_U > Q$

Consensus Approaches: Alternatives

- **Weighted vs. equal votes**
  - Equal votes: each node has a vote with $weight = 1$
  - Weighted votes: nodes get assigned different weight, allows decreased message number by first asking nodes great weight
- **Static vs. dynamic voting**

    - Static: Q_R and Q_U do not change
    - Dynamic: Q_R and Q_U are adjusted to new Q in case of node failures or network fragmentation

- **Tree Quorum**
    - Nodes are hierarchically structured and separate quorums are defined for each level

Majority Consensus

- "‘Origin"’ of all consensus approaches: equal votes and static
- Works in case of node failures and network fragmentation
- Supports synchronization based on timestamps (without locks)
- Basic principles:
    - Communication along logical ring of nodes $\rightsquigarrow$ request and decisions are passed on from node to node
    - Quorum-Rules grant consistency in case of concurrent conflicting operations
    - With equal votes: $Q_U > Q/2$, i.e. majority of nodes in ring has to agree to operation

Majority Consensus: Procedure

1. **Origin node** of operation/TXN performs update locally and passes on changed objects with update timestamp to next node in ring
2. **Other nodes** vote
    - **reject**, if there is a timestamp conflict $\rightsquigarrow$ abort message is sent back to previous nodes, TXN is restarted at origin node
    - **okay**, if there is no conflict, request is marked *pending* until final decision
    - **pass**, if there is no timestamp conflict but a conflict with a concurrent update which is also *pending*
3. **Last node** which votes okay and by that satisfies quorum rule passes on commit to all nodes (backward and forward), update is propagated to all further nodes, pending updates are finalized on all previous nodes

Data Patches

- Problem: resolution of inconsistencies after node failures/ network fragmentation
- Idea: application-specific rules designed during database design $\rightarrow$ individual rules for each relation
- Rules:
  - Tuple insert rules: to add new tuples (keep, remove, notify, program)
  - Tuple integration rules: merge values of independently changed tuples with the same key (latest, primary, arithmetic,notify, program)

Snapshot Replication

- Snapshots: define (remote) materialized view on master-table
- Similar to primary copy, but also allows operations (filters, projection, aggregation, etc.) as part of view definition
- Synchronization of view by explicit **refresh** (manual or frequent)
- Handling of updates:
  - **Read-only snapshots**: updates only on master table
  - **Updateable views**: requires conflict resolution with master table (e.g. by rules, triggers)

Epidemic Replication

- Updates possible on every node
- Asynchronous forwarding of updates to "‘neighbours"’ using version information (timestamps)
- E.g. possible with Lotus Notes

Lazy Replication

- Updates on all nodes possibles
- Each node can start separate TXNs to perform updates on other nodes asynchronously
- Requires (application-specific) conflict resolution strategies
- Works in mobile scenarios, where node can connect/disconnect to/from the network